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DESIGN PARAMETER ANALYSIS OF THE BOGIE TRACK SURFACE PRESSURE IN PEATLAND FOREST OPERATIONS

Master of Science Thesis

Examiner: prof. Kari Koskinen
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ABSTRACT

LEENA JARKKO: Design parameter analysis of the bogie track surface pressure in peatland forest operations
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This thesis studies the effect of different design parameters on surface pressure under a wheeled forestry machine equipped with bogie tracks. The chosen design parameters were bogie dimensions, especially the distance between wheel hubs, an additional auxiliary wheel between the bogie wheels, bogie balancing and peat soil moisture content.

The thesis introduces several variables to be considered if constructing a realistic simulation model for peatland forestry operations. A wide introduction to soft terrain logging gives the base to further studies. Rut formation is based on complex terramechanical theories and the machine dynamics. The mechanisms of rut formation and the effect of heavy machinery on forest soil were also included.

Widely used equations for surface pressure don't take the effect of soil type nor compaction into account. Most of the equation are constructed for silt or clay soil, and it seems, that they are not necessarily applicable for peat soil. The resulting surface pressure values are not fully comparable, and they should only be used as a reference, when comparing different forest machines to each other. The lowest value is about 9 times smaller than the largest one. Most of the surface pressure values exceed the widely used limit of 50 kPa for peatland operations. The resulting exact values for surface pressure should thus be used carefully. Forming a valid surface pressure equation for peat soil has proven to be extremely challenging. Field testing seems to be an adequate way to study the machine properties before suitable simulation models are available.

TIIVISTELMÄ

LEENA JARKKO: Teliakselin telan pintapaineen suunnitteluparametrianalyysi turvemetsän puunkorjuussa
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Avainsanat: kääntöteli, pintapaine, turvemaasto, urien muodostuminen

Diplomityö tutkii eri suunnitteluparametrien vaikutusta teliakselilla ja irrotettavilla teloilla varustetun metsäkoneen pintapaineeseen. Valitut suunnitteluparametrit olivat telin dimensiot, erityisesti pyörien napojen välinen etäisyys, lisäpyörän asentaminen teliakselilla olevien pyörien väliin, telin tasapainotus sekä turvemaan kosteuspitoisuus.

Diplomityössä käydään läpi muuttujat, jotka pitää ottaa huomioon realistista simulointimallia rakennettaessa, kun kyseessä on turvemaaston puunkorjuu. Laaja katsaus pehmeän maaston puunkorjuuseen antaa pohjan tuleville tutkimuksille. Urien muodostuminen perustuu monimutkaisiin terramekaanisiin teorioihin ja telin dynamiikkaan. Uran muodostumisen mekanismit ja raskaan korjuukaluston vaikutukset metsien maaperään käydään myös läpi.

Laajasti käytössä olevat yhtälöt pintapaineelle eivät ota maaperän tyyppiä tai painumaa huomioon. Suurin osa yhtälöistä on muodostettu siltti- tai savimaalle, eivätkä ne siten ole välttämättä käyttökelpoisia turvemaan tutkimiseen. Tulokseksi saadut pintapainearvot eivät ole täysin vertailukelpoisia, ja niitä on suositeltavaa käyttää vain referenssiarvoina eri metsäkonemalleja vertailtaessa. Pienin pintapainearvo on noin 9 kertaa pienempi kuin suurin. Suurin osa arvoista ylittää yleisesti turvemaaston kantokykynä pidetyn 50 kPa:n. Tulokseksi saatuja tarkkoja arvoja pintapaineelle kannattaa siten käyttää varoen. Todenmukaisen laskentamallin muodostaminen pintapaineelle turvemaastossa on osoittautunut äärimmäisen vaikeaksi. Asianmukaisten simulointimallien puuttuessa kenttätestit vaikuttavat olevan tarkoituksenmukainen tapa tutkia koneen ominaisuuksia.

PREFACE

Haluan kiittää kaikkia, jotka ovat jaksaneet kannustaa välillä mahdottomaltakin tuntuneessa matkassa kohta diplomi-insinööriyttä. Haluan kiittää diplomityöni ohjaajaa professori Kari Koskista sekä John Deere Forestry Oy:n Timo Laitista ja Jouni Jämsää, jotta joustivat ja antoivat tukea diplomityön aiheen muokkaantuessa prosessin aikana. Kiitos John Deere Forestry Oy:lle, että sain mahdollisuuden tehdä diplomityöni metsäkoneiden maailmasta. Kiitos myös koko perheelleni, että ovat olleet tukenani aina.

Diplomityöprosessi oli itsessään upea seikkailu. Koko opiskeluaikani TTY:llä on matka, joka on nyt valmis. Kiitos kaikille niille tahoille ja ihmisille, jotta ovat osaltaan hidastaneet valmistumistani tarjoamalla kokemuksia ja ihmissuhteita, joita en olisi muuten saanut. Haluan kiittää kaikkia, joiden kanssa olen saanut olla yhdessä tällä matkalla ja erityisesti heitä, jotka ovat valaneet minuun uskoa siitä, että kyllä minäkin joskus vielä valmistun. Haikea, mutta tyytyväinen olo.

Tampereella, 19.11.2018

Leena Jarkko

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LIST OF SYMBOLS AND ABBREVIATIONS

CTL	Cut-To-Length, timber harvesting method, where the whole tree is processed to assortments on the site
DEM	Discrete Element Method
FEM	Finite Element Method
GPI	Ground Pressure Index
LiDAR	Light Detection and Ranging
MMP	Mean Maximum Pressure
NGP	Nominal Ground Pressure

α	slope angle in degrees
γ	unit weight of soil
δ	radial deflection of the pneumatic tyre under load
θ	variable wheel angle
θ_f	soil friction angle
θ_s	static wheel angle
μ	ratio between bogie tractive force and bogie load
σ	applied load
σ-$\chi\psi$	effective load
χ	desaturation factor representing the fraction of the surface area in any plane through which the matric tension acts
ψ	soil matric water potential

A	contact surface area
A_l	rigid area of link track cleat in proportion to the whole track area
B	track width
B_f	foundation width
c	soil cohesion
C’	effective cohesion of the soil type
d	outer diameter of a pneumatic tyre
D_h	hydraulic diameter
F	bogie tractive force
F_e	bogie front axle load
g	gravity acceleration
G	bogie load
h	tyre carcass height
i	bogie gear ratio
l_{AX}	axle base
k	stiffness coefficient
k_c	cohesive modulus
$\hat{k}$	Meirion-Griffith variable
k_Φ	frictional modulus
k'_c	stiffness factor, cohesive
k'_Φ	stiffness factor, frictional
L	distance between the wheel hubs
r	wheel radius
$\hat{m}$	Meirion-Griffith variable
M	machine mass

n	exponent of soil deformation
n_r	number of axles
$\hat{n}$	Meirion-Griffith variable
N	number of passes
p	surface pressure
p_c	contact pressure
p_i	inflation pressure
q	load
r	unloaded radius of the tyres
r_1	unloaded radius of tyre 1
r_2	unloaded radius of tyre 2
S	soil shear strength
s	average penetration
t_t	track pitch
V	vehicle velocity
W	machine weight
W_{wheel}	wheel load
y	perpendicular distance between the point of bogie bearing point and the line connecting the wheel hub centers

1. INTRODUCTION

The aim of this thesis is to investigate the crucial factors that have an impact on the surface pressure between the ground and the tracks of a wheeled cut-to-length forest machine equipped with removable tracks. The basic structure of a forestry machine used in this thesis, is a midsize forwarder that weights approximately from 18 500 kg to 20 000 kg when empty and to load increases the machine weight up to 15 00 kg. Adding tracks increases to machine weight a few tons. A forwarder is considered as the subject machine due to its larger machine weight compared to a harvester.

Terrain damage caused by mechanized timber harvesting operations has become a wide problem to the forest industry. Chapter 2 introduces the theoretical background of soil mechanics. Different soil mechanics theories are the foundation of this thesis. Heavy machinery causes the soil to compact and leaves marks to the terrain. The goal is to find a basic design to a forestry machine that is capable to operate in soft terrain (especially on boreal drained peatlands) without forming unacceptable ruts and trails by varying the design parameters defined in chapter 3. The goal is to find the factors that have an impact to the rut formation. Surface pressure seems to be one of the driving features. The thesis focuses on finding the factors that enable mechanized timber harvesting in soft soil terrain. The greatest challenge is to adapt machine work into low bearability terrain. Rarely contractors can acquire a machine design especially for condition of low bearability, but the existing machines must be adaptable and versatile. The period of frozen soil has shortened due to the global warming and more and more harvesting sites have become soft soil sites even during the winter season. Additionally, more and more peatlands are drained and harnessed to timber production. The industry demands a constant flow of timber around the year, so some of the sites must be harvested while they have low bearability. An additional issue to be studied is how to improve trafficability of the forestry machines.

This thesis focuses mainly in peat soil. The characteristics of peat soil are problematic. Cohesive soils are easier to define, because their consistency can be described. Peat soils consistency has proven to be very challenging due to its fibrous and heterogeneous substance. Peat also contains a large portion of organic material; which consistency is hard to define, and the moisture content varies greatly according into the weather conditions. One of the main challenges is to simulate the soil. The consistency of different soil types varies greatly, so a basic generalization can’t be done. Mechanized timber harvesting has a large impact on the soil. Chapter 4 introduces the mechanical effects to the soil as a material when forest soil is exposed to heavy harvesting machinery.

The magnitude and distribution of pressure under the track can be simulated with a simplified model. This thesis aims to find the determining factors in the structure of the bogie and the tracks that minimize the surface pressure of the machine. Additionally, other changes to the machine layout can be done. The surface pressure is commensurate with the contact area of the track. By extending the distance between the wheel hubs or widening the track, the surface area of the track increases and the surface pressure should decrease. Chapter 5 focuses on the key design parameters that must be considered for soft soil machinery.

A model for field testing is introduced in chapter 6. Due to unexpected delays, the actual field testing could not be included in this thesis. The chapter demonstrates the basic structure for small-scale and complete machine studies to assist potential future testing. To verify the simulation results and theory related to the topic, field tests for rut formation could be carried out. In this project the measurement work is dismissed, because of the possible errors occurring due to inconsistent soil conditions. For the measurements to be reliable, the conditions must be repeatable.

1.1 Mechanized timber harvesting

The use of machines in timber harvesting has revolutionized the industry. The machinery is an expensive investment but normally its repayment period is relatively short and return on investment high. While the development of forestry machinery has transformed the timber harvesting, efficiency has become more and more important. Challenging terrain decreases productivity. Although larger machines can process more timber, the weight of the machines has become a crucial factor, when selecting a machine. In low-bearing terrain, the surface pressure produced by the forestry machine must be significantly lower than in well-bearing soil, to prevent the machine to sink in the soil and causing unacceptable terrain damage.

Normally the harvesting is based on two different harvesting methods; full-tree and cut-to-length methods. In the full-tree or the whole-tree method the entire tree is cut down and transported to the roadside landing. The tree is transported with cables or skidders and the tree is buckled and delimbed there before further transportation. The cut-to-length harvesting method is most common in Scandinavia [1]. In the cut-to-length system, the whole tree is processed to assortments in the harvesting site before the timber is transported. The cut-to-length harvesting system is based on two different machine types with different purposes. A harvester is a machine that is responsible for the felling and of on-site processing the trees. Figure 1 gives an example of a harvester. The basic structure of a harvester of the largest manufacturers is roughly the same. A forwarder transports the timber to roadside landings, where the trucks can pick it up. Figure 2 gives an example of the most common forwarder design.

Figure 1. *An example of a harvester; John Deere 1270G.* [2]

Figure 2. *An example of a forwarder; John Deere 1510G.* [2]

In the cut-to-length (CTL) harvesting system, the whole tree is processed by a harvester to different assortments in the felling site and different parts of the stem are cut to most beneficial lengths according to the trunk diameter. In Figure 3 is shown a typical division of the processed stem.

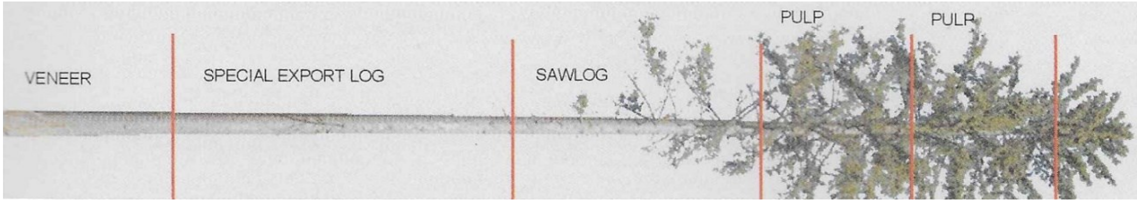


Figure 3. *Scaling of stems. Different assortments are used for different purposes.* [3]

The different timber assortments are moved with a forwarder to roadside landings, where they are collected and moved to manufacturing factories and processing plants. The CTL machinery is more expensive than the full-tree machinery, but has a better revenue. [4]

1.2 Soft terrain logging

Climate change and global warming cause the dry winter season in boreal forests to shorten and the planned harvesting season might have to be changed annually [5][6]. If soft terrain sites cannot be harvested in the planned schedule, the profitability of the forest decreases. Decreasing seasonal variation in timber harvesting is a key feature to more efficient forest management. Peatlands are also harnessed to timber production: the amount of soft soil peatland sites compared to all the sites is 33 % in Finland. It represents 8644 ha of land. [7]

The bearing capacity of the ground depends on the chemical composition and humidity of the soil. Rainfall and thus the water table influence the water content in the ground. The water content can be high and the ground still well-bearing, if the temperature of the soil is low enough and the water freezes. Time of the frost heave is increasing every year and because some felling sites can only be harvested in the winter when the ground is frozen and well-bearing, it causes trouble to the demand for the continuous flow of timber to the industry. The demand has created a need to utilize also peatlands to timber production. More and more wet peatlands are drained to enable mechanized timber harvesting in the areas. Challenging harvesting conditions require new features from the machinery. The forestry machines must be able to operate in variable terrain conditions that also include soft soil areas. If the mobility of the machine and maximum load it can carry without forming unbearable ruts can be achieved, the routes shorten, and the transportation time decreases. This reduces fuel and personal costs. [8]

A typical Scandinavian forest is a boreal forest. A dense forest increases the soil bearability, because the tree roots form a network under the surface layer of the ground.

Thick undergrowth, especially sprigs, may also have a positive effect to the bearability. Normally the sites that tend to have softer soil are harvested during the winter when there is frost and the snow protects the soil surface layer from larger damages. Snow can also be problematic if the snow cover is too deep and there is a risk of getting stuck with the harvesting machinery or the isolating snow cover prevents the ground to freeze. Snow can pile up between the tracks and the wheels and cause the track to over-tighten.

The cost of the logging is dependent on e.g. operating speed, the amount of timber forwarded in a load and the time spend in extra activities, including ditch crossings and strengthening the strip roads. [3] The increasing demand of timber has laid claim to utilize more and more demanding logging sites to timber production. A steady, year-round flow of timber is crucial for the forest industry future investments. If the soft soil sites can be harvest also during the summer, it can balance the timber supply, machinery operating time and work power need during the year. More and more peatlands are drained and harnessed to timber production. Drained peatlands demand different kind of machinery. Because the soil is softer, the heavy machinery must have better floating abilities than conventional machinery. Normally the features are improved by addition equipment, because special machinery for limited harvesting areas is not cost-worthy.

The Finnish government own research expert company Tapio Ltd. has coordinated a guidebook for sustainable forest management. Tapio Ltd. has gathered recommendations for timber harvesting in low-bearing logging sites and best practices for sustainable forest management. Low-bearing logging site require special attention in the planning and in the actual logging actions. Planning the logging process thoroughly in advance, most of the problems with low bearability can be avoided. The planning should focus on the placing of the strip road so that the most challenging spots can be avoided or passed only once. [9]

Site planning is a crucial part of ground preservation. Because there is always a risk of getting stuck or breaking the machine, site planning must be done properly. Site planning helps to minimize the ruts, if the strip roads are well planned. Positioning the strip roads should be done according to the site terrain characteristics. Figure 4 shows the basic structure of a strip road network in a felling site. The connective roads between the strips should be placed to well-bearing ground and soft soil areas should be harvested in minimal passes. The irregularity of the terrain may affect the placing of the strip roads. *A* and *E* represent the main strip road that is placed on well-bearing ground and can be crossed multiple times.

If the soil has low bearability or is otherwise sensitive, the passed should be minimal. The area most prone to sink should be avoided. Topography and water level maps can be utilized to find the risky spots in the sites. Avoiding multiple passes may require further planning of the placement, size and amount of the roadside landings and forwarding mixed load of different varieties of timber at a single pass. If the trail must be passed multiple times, the strip roads should be cleared out wide enough and the operator should utilize the whole trail width. Turns should be minimized, and the strip roads should be as straight lined as possible, because turning increases the shear stress impacting the ground, thus resulting in greater rutting. *B* and *D* are connecting strip roads that are placed according to the shape of the site. The form a loop starting and ending to the main strip roads, so they can be passed as few times as possible. *C* represents a reverse strip road that is used when a loop is not appropriate, for example when there are natural obstacles. The load size and the center of gravity can be adjusted according the bearing capacity of the ground. The harvester operator can also reduce the soil disturbance by spreading logging residue to the trails and cutting the stumps as short as possible. Slash reinforcement of strip roads protects the surface layer and raise the amount off passes before any unacceptable terrain damages occurs. Repetitive loading places new requirements for the acceptable surface pressure of the machine. In the ideal situation, a strip road is collected in single pass. [3]

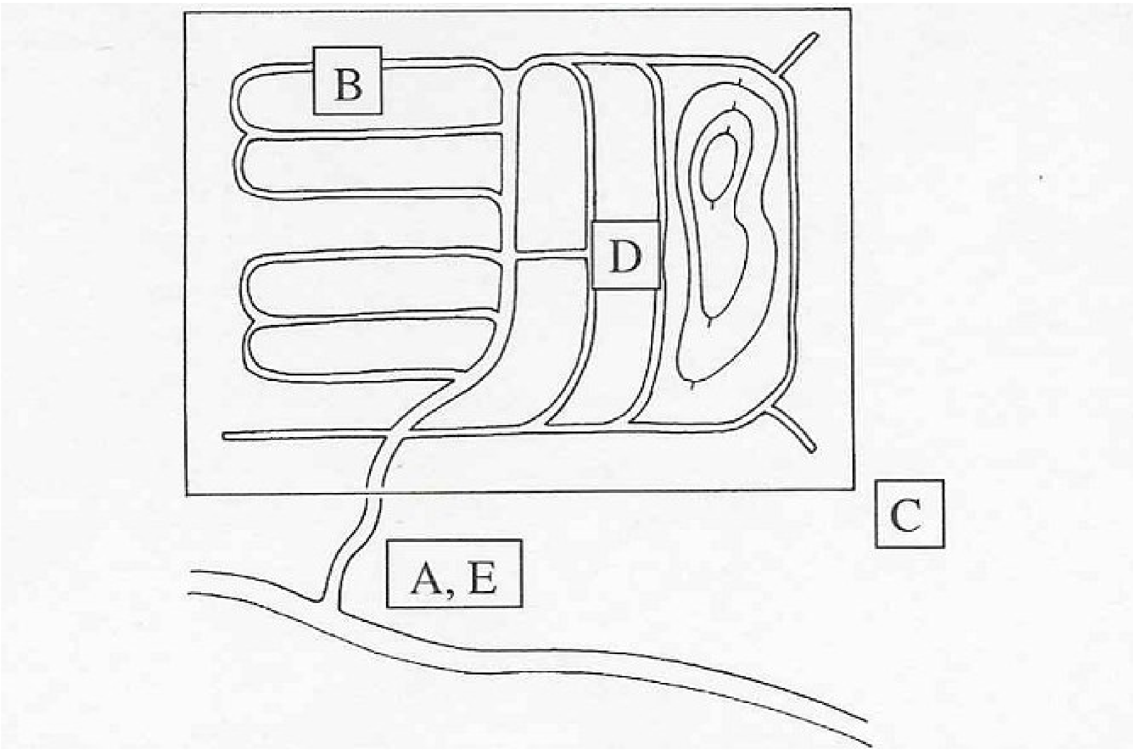


Figure 4. *Schematic picture of strip roads.* [3]

It must be possible to fell to whole sector with the same machine chain and in the same season. The soil bearing capacity is one of the key factors when dividing the site to sectors. Areas with dense tree stand are more likely to have usually greater bearing capacity than areas with less trees, because of the network of tree roots. The machinery must be chosen according to the terrain conditions and timber characteristics. The machines must be the suitable size and equipped with the suitable accessories.

Forestry tyres can roughly be divided to two types according to their thread pattern: track pattern to machines that will be equipped with track and traction pattern to machine that need better tyre traction. The tyres should be chosen according to the terrain conditions they are used in and the tread pattern should also be chosen according to the application conditions. Tyre manufactures offer special tyre models for track use. Forestry tyres are specially designed to operate in forest terrain. They are wide, and the inflation pressures are lower than when operating in rigid terrain. The bearing capacity of a tyre depends also on the structure of the tyres. Forestry tyres most commonly are either radial-constructed or diagonal-ply belt tyres. The ply number also affects the characteristics of the tyre. [10][11]

Low inflation pressures may decrease the surface pressure when the contact surface increases and the pressure is spread to a wider area. Tyre manufactures do not guarantee that the tyres perform with lower inflation pressures than reference values, and the risk of breaking the tyre is substantially larger. If using tracks, the inflation pressure is normally higher so the track stays in place. Tyre manufactures give reference values also for inflation pressures in track use. [11] Tyre dynamics models are usually developed by the car industry and thus focus mainly on the behavior of the tyre with a rigid ground, asphalt etc. Along with the development of radial tyres, the deflection rate is proven to vary according to the structure of the tyre. [12]

Figure 5. *Some examples of removable track for wheeled CTL machines.[13]*

Wheeled forestry machines are often equipped with removable tracks that increase traction and flotation in soft soils. Removable tracks are used to increase the surface area of the ground contact. Larger contact area provides more flotation, so the machine can work in more challenging terrain condition. Terrain conditions can vary from snowy to susceptible peat bogs, and different terrains need a different set on tracks. Figure 5 shows different designs of conventional removable tracks. In this thesis, the track system covered is a basic link track system. The track is mounted between two forestry tyres suitable for track use. In this thesis, only a basic structure of a track model fitted on top of the tyres, because the commonly-used solutions are roughly the same. Also, other solutions, e.g. excavator tracks for wheeled forestry machines, have been introduced to the market, but they aren’t covered in this thesis.

The track is composed of metal track shoes that are attached to each other with metal links at the end of the track plate. The size of the side linkage is chosen according to the size of the tyres and when operating in challenging operating conditions, the link size can be increased. The track itself has guides or side supports that keep the track on top of tyres and prevent the track to get misaligned. Figure 6 shows the evolution of a basic link system bogie track. Typically, tyre-mounted track systems don't have a tensioning system, and the amount of links and plates defines the length and thus the tension of the track. The track itself has to be designed the way that it won't get misaligned, because there are no aligning support rollers. Inefficiently installed tracks cause unwanted vibrations and wear to the components, including the tyres. The links should be in the same level as the rolling radius of the wheel, so the track travels the same distance that the wheel and the slip between the track and the tyre is as little as possible.

Figure 6. *(a) The construction of a bogie track with rolling radii for the linkage system (r) and tire surface (R). (b) A track with the old linkage system, and (c) a track with the newer system (ECO-Track).* [14]

Track manufactures offer special applications to soft terrain. Equipment for sensitive and soft soils are available with extended plate widths. These tracks feature upturned edges to reduce soil damage whilst steering and they reduce root cutting, making them particularly suited to thinning operations. The plate itself is normally as flat as possible, so the soil is disturbed as little as possible [15]. The use of tracks is reasonable when the surface pressure must be maximized. Tracks add the surface area the machine is in contact with the ground. It must be considered when choosing tracks, that snowy conditions require a different kind of track was soft soil operations. Snow and certain kind of mud can get compacted between the track and the tyres and cause the track tension to increase. It may result in bogie, transmission, and tyre or track failure.

The tracks must be chosen according to the conditions they are utilized in. The same set of tracks rarely is the best solution in drained peat lands in the summer and in snowy winter conditions. Track manufactures have different kinds of profiles to altering terrain condition to meet the requirements of the industry. Due to the challenging logging conditions, the track must endure different kinds of terrain in the same site. Plots do not necessarily follow the boundaries of the landscape, and the terrain can vary significantly in the site. This requires the machinery to be versatile.

There are various features in the track that qualify the track to be used in certain conditions. The profile of the track shoe and their spacing affect the total area and thus the surface pressure of the track. Although it would seem logical to minimize the track spacing and maximize the surface area of the track, a too dense track doesn't clean itself as the loose material might get caught between the track and the wheels. It may result as over-tensioning the track and lead to serious transmission or bogie failure.

If the spacing of the track shoes is small, the effective contact area of the track is larger, but loose material stuck inside track is not able to fall out. Different soil types behave differently, because of their compaction and friction characteristics. Even if widening the track would increase the contact area with the ground and thus decrease the surface pressure, the track rarely can be widened due to the limitations set by the machine itself, the felling site or regulations regarding machine transportation. The dimensions of the machine have to be a small as possible and widening the tracks will eventually lead to problems in fitting the machine in the narrow logging roads, especially in thinning sites. Because the tracks are an accessory, the machine has limitations for the dimensions the track can have without interfering the machine movement. The clearance between the track and the machine frame is restively small. The tracks are normally designed and produced by an independent company and the track must fit the machines of various manufacturers. Compromises must be made.

1.3 Soft terrain properties and properties of peat soil

The Finnish government funded research institute Metsäteho has created a classification for bearing capacity of thinning sites in peatlands [16]. The classification is meant to classify harvesting conditions in thinning sites in peatlands. It can only be applied to wheeled forestry machine equipped with removable tracks, not to machines with excavator tracks. Final felling sites are not covered in the model. A large wood density in porous peat lands increases the bearing capacity of the soil, because of the increasing number of roots in the area. Table 1 introduces the basic idea of the classification.

Table 1. *The classification according to the average off-road transportation distance. Translated from [8]*

Average off-road transportation distance	Level of stress of the logging road network in the classification
less than 100 m	low
100 – 200 m	moderate
more than 200 m	high

Table 2. *Requirements for the machinery in different terrain classes. Translated from* [16]

Required harvesting classification	Ground surface pressure	Bearing class ID
standard	> 50 kPa	0
improved	≤ 50 kPa	1
floating	≤ 40 kPa	2
extra floating	≤ 30 kPa	3

In Table 2, class 0 sites have the most bearing capacity and class 3 represents the most challenging sites to harvest. A site is considered a soft soil site, if the bearing capacity of the soil is less than 50 kPa. Some sites are so challenging that they are recommended to be harvested in the winter season, when the ground is frozen and the bearing capacity of the soil increases. The classification of the site can vary during the frost heave and because of extensive rainfall and the water table or the depth of the peat deposit. Table 3 represents different kinds of harvesting sites. The load rating and the wood density of the sites determine the conditions the site should be harvested in. Some sites are so soft that the harvesting should be done only during frozen ground. [16]

Table 3. *Categorization for harvesting conditions of thinning sites in peatlands. Translated from* [16]

<table>
<tr><td rowspan="3">Wood density in the harvesting site (m³/ha)</td><td colspan="3">Estimated level of stress on the logging road network based on the location of the storage landings and the shape and size of the site *)</td></tr>
<tr><td>Low</td><td>Moderate</td><td>High</td></tr>
<tr><td colspan="3">Load rating **)</td></tr>
<tr><td>> 170</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td>120 – 170</td><td>2</td><td>3</td><td>WINTER</td></tr>
<tr><td>< 120</td><td>3</td><td>WINTER</td><td>WINTER</td></tr>
<tr><td colspan="4">Corrections to the harvesting condition classes:</td></tr>
<tr><td colspan="4">Water table:
In sites, where <u>the ground water is less than 25 cm from the surface of the bog</u>, a higher load rating should be used.
If <u>a more than 4-week dry season precedes the harvesting operations</u>, the load rating decreases a level.</td></tr>
<tr><td colspan="4">Depth of the peat layer: In sites, where <u>the peat layer is less than 75 cm</u>, the load rating increases a level.</td></tr>
<tr><td colspan="4">*) Approximate average off-road transportation distance in peatlands:
low: < 100 m, moderate: 100 – 200 m and high: > 200 m
**) It is required that the logging residue is left on the strip road and the spots with a small area or critical for the strip road network are strengthened with logging residue or in other manner</td></tr>
</table>

Defining the properties of peat has proven to be challenging, because of the natural variation in the composition of peat. Peat can contain a high amount of organic matter, either living, decomposed or partly decomposed. Also, the water content can vary greatly. Thus, defining peat via a mathematical model can be problematic. Fibrous material forms the base structure of pure peat, but natural peat soil can contain up to 97 % organic material. [17][18] In peatland forests the soil is also strengthened by the roots of the trees and the underbrush. Peat soil has a substantial moisture absorption capacity. The fibrous consistency of peat forms broad pores to the soil and the pores are usually filled with air if the soil is dry. The consistency of pure peat is thus spongy. When the peat is loaded, the pores compact and deflate. The compaction of the peat soil is related to the moisture content. Wet soil doesn't recover from the loading as well as peat, because the fibers of the peat get stuck together and the texture of the fibers is easily broken when wet. If the pores collapse due to the loading, it can have an impact on the rut formation. Wet soil tends to have a greater tendency to suffer from irreversible compaction than dry soil. [19]

1.4 Terrain damage and nature disturbance due to mechanized forestry

In modern-day forestry, more and more attention is paid to the environmental impacts of mechanized timber harvesting. The harvesting impact must be minimal. [20][21] Heavy machines cause soil compaction and may destroy the micro vascular system that enables the water and nutrient supply to the trees and other vegetation. Root and tree stand damage interfere the forest's regrowth and thus the efficiency of the land decreases. [22] Different felling sites, both thinning and final felling sites, require machinery that preserves the terrain and nature as much as possible, so the felled area can regenerate. The effects of off-road traffic on the terrain has been widely researched. Soil compaction due to forestry machine operations damages the roots of living trees and decreases the growth-rate [23]. The aim of present-day forestry is to reduce ground disturbance as much as possible.

One of the biggest concerns in mechanized forestry after exhaust discharges and other kinds of emissions, is the formation of ruts and trails on the terrain. Figure 7 shows an example of ruts made by heavy traffic during logging operations. Forestry machines are large so that they can process efficiently large amount of timber, but the large size normally correlates with a heavy machine. A heavy machine inflicts soil compaction in the machine-operating trails and causes ruts to form. Deep ruts interfere with the forest ecosystem and might influence the regrowth of the area. Forest machines can also damage living trees that are not cut down. [22] Also the visual aspects must be considered due to the increasing interest in recreation areas. The depth and the width of the ruts must be as small as possible.

Figure 7. *Ruts created by a wheeled tractor during logging operations in the silt loam soil of a coppice oak forest in the Chianti region, Tuscany, Italy. Visible damage includes broken roots, soil displacement and compaction. Soil compaction is so extreme that water does not percolate into the soil and induces anoxic conditions in the top layer. During the rainy season, ruts become preferential flow paths and result in erosion.* [22]

Rutting affects the soil in various ways. The soil can be pushed aside, and the lower layer exposed if the surface layer is damaged. The soil gets compacted and thus the vascular system of the soil is disturbed. Loose soil gets washed away by the rain and erosion occurs whilst the amount of nutrients reduce significantly. [19][24] Many countries have legislated the acceptable level of terrain damage that can be tolerated in forests harvested mechanically. It is stated in the Finnish Government Decree on Sustainable Management and Use of Forests (1308/2013) based on the Finnish Forest Act (1093/1996) that *in improvement cutting and special felling sites the proportion of the average amount of ruts must not exceed 20 % of the total length of the logging road in mineral soil and 25 % in peatlands. A terrain damage is considered a rut, if in mineral soil its length exceeds 1 m and its depth exceeds 10 cm from the base ground level. In peatlands, a terrain damage is considered a rut if the soil is sliced off at least 20 cm deep and 1 m long*. The Finnish Forest Act also states in chapter 2, section 5 that *felling and the measures to be performed in connection with it shall be implemented in such a way that the tree stand left to grow in the felling area is not damaged. Damage to the tree stand growing outside the felling area is also to be avoided when carrying out the felling operation and the measures* *associated with it. In addition, such damage to the terrain that results in deterioration of the growing conditions for the tree stand shall be avoided.* [25]

One of the rarely acknowledged factor in rut formation is the skills of the machine operator. An untrained operator can leave deep ruts even in well-bearing soil, if the machine is steered sharply and the site planning is neglected. The effect of skilled machine operator on rut formation can be massive. A professional harvester operator leaves the logging residue on the logging roads, so the ground surface is more protected while passed. Pulp timber can also be inserted to the strip road to increase bearing capacity in softer zones.

The machine must have an ability to float in the forest and damage the environment as little as possible. If the surface layer of the ground is broken, the bearing capacity of the soil decreases significantly [26].The basic principle to increase surface pressure is to increase the surface area that is in contact with the ground. It can be done by widening the tyres, lowering the tyre pressure or utilizing special equipment, e.g. tracks. By equipping a standard machine with removable tracks suitable for soft terrain or wide forestry tyres, costs can be reduced, and the machines are more versatile.

If the harvester breaks the soil surface layer, the passage of the following forwarder becomes more and more challenging as the soil bearability decreases significantly. Even though adding track may increase the risk of shearing, when turning the machine, thus the surface area in contact with soil is larger. Tracks lower the surface pressure significantly, so they still decrease the possibility of puncturing the soil surface. The terrain can also be protected against machine-based damages with additional equipment. The reason to use additional equipment is to protect the soil in rough conditions and to ease the machine work. The most fragile areas can be covered before the machines passes them. Additional equipment increases the costs of the felling, but they help to preserve the terrain and raise the amount of the potential passes on the strip roads. That can improve the productivity of the site, if the time spent in reinforcement is less than the time that would be spent on avoiding the risky spots. Adequate site planning and a skillful machine operator are an important part of preventing terrain damages.

The terrain can be reinforced with additional material. The tree should be trimmed to the machine-operating road, so the slash protects the surface layer of the soil. Pulp timber is commonly added to soft spots to increase the bearing capacity of the ground and ease the crossing of challenging obstacles, ditches etc. If the ground surface is particularly sensitive, also removable mobile protection mats, bridges or other kinds of equipment can be used. Protective equipment and material act as a cover that reduces the shear force the soil affecting the soil and distributes the machine load more evenly. The transportation of these items demands resources, but they protect the soil surface layer quite efficiently when installed correctly.

2. SOIL MECHANICS

Different soil types have different physical characteristics. Soil has material properties any other material would have. Different soil types can vary greatly in shear resistance, bulk density, Young's modulus, and in the internal structure. The deformation of the soil can happen with various methods. Soil deformation can be elastic or plastic, and everything between. Some types are more cohesive, and others consist of granular material. Different layers of soil interact with each other and can have a different method of compaction. The soil consistency changes according to the depth. Normally the ground is covered with loose material, debris or similar and the soil classification is done according to the main soil type in the area.

Simulating forest soil has proven to be challenging. Soil can be simulated if it is somewhat homogeneous (e.g. asphalt, sand, gravel) [27][28][29] and the consistency of the substance is known. Although different types of forest soil, that have been influenced by mechanized harvesting, have been researched, so far, the research has mainly focused on the chemical composition of the soil or the renewal of the natural habitat after the forestry operations. Simulating realistically drained peatland would require extensive and thorough research that focused solely on the topic.

The effective contact length can be larger in soft soil than in firm soil. When studying the contact pressure under an off-road vehicle, also the characteristics of the soil must be taken into account. The contact area can be challenging to define, because of the deformations occurring both in the soil and in the tyres or tracks of the vehicle. The soil deforms under the pressure produced by the machine and the sinking of the track increases the contact area in front of the machine while driving forward. If the axle load is large enough, the track itself can deform.

2.1 Theoretical surface area

The inflation pressure of the tyre also has an effect to the effective contact surface that has contact with the ground. When the inflation pressure is lower, the tyre deforms and the contact area increases. In simulation model with only tyres the surface area can be calculated with a 15 % deflection from the tyre section height and a twentieth part of the diameter increase in width. Figure 8 shows the basic principle of the effect of decreasing the tyre inflation pressure. The surface area was multiplied with two to represent a pair of tyres. The deflection rate impacts the contact area of the tyre, and thus the sinkage height. [10][12][30] Because the deflection of the tyres is considered to be a constant 15 % from the tyre section height and independent from the tyre load, the surface area calculated this way is just a rough assumption. The actual surface area of a forestry tyre would be smaller, because of the tread pattern. Tyres that are intended to have a lot of friction with the ground have a high tread pattern and thus the surface area can be quite different than for a plain tyre. Soft soil evens out the differences the tread pattern has, because of the sinkage. The behavior of forest tyres is widely researched and Saarilahti has made a clarifying summary report of the different calculation models for forestry tyre surface pressures in 2002 [31].

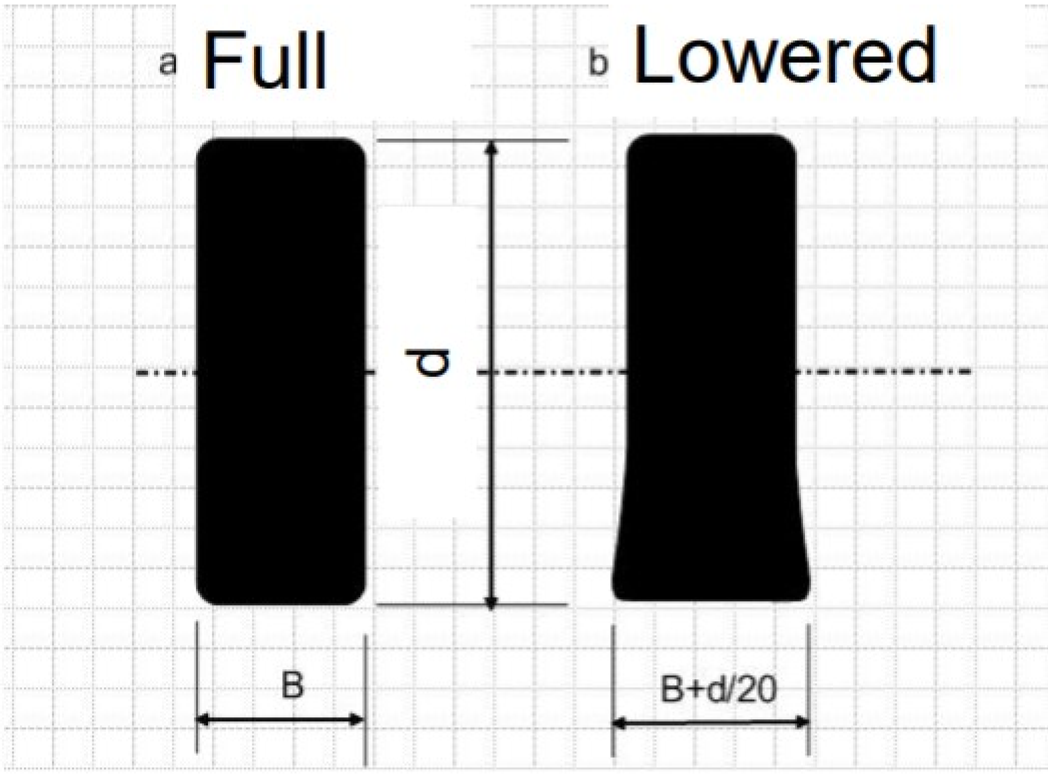


Figure 8. *Increase in tyre width with a lower inflation pressure* [32]

The surface area for the tracked simulations cases can be defined in a similar way than the surface area for the tyre model. For an individual track element, the surface area is the plate width multiplied with the length of the plate. Thus, the contact area for the whole track is the amount of the track elements simultaneously in contact with the ground multiplied with the surface area of a plate. The amount of plates that are in contact with the ground in any given time varies according to the stiffness of the soil, the tension of the track and the possible deformation of the track under heavy loads.

2.2 Surface pressure

The surface pressure between the track and the soil seems to be the crucial factor when considering the impact, the machine has to the terrain. The main factors impacting the magnitude of surface pressure under the track are machine weight, center of gravity, area of the track in contact with the ground and the shape and dimensions of the bogie. The shape of the track shoe influences the contact area of the track. Also, the spacing of the track shoes alters the surface pressure. The load is unevenly distributed on the surface area under the wheeled forestry machine. The axle load is distributed by the wheel hubs to the tyres. The shape of the soil stress profile under the track depends on the tension on the track, the inflation pressure and thus the deformation of the tyre and on the total area in contact with the soil.

Most of the research in forestry machines has been done with forestry tyres. Although off-road tracked vehicles have been researched extensively, most of the research focuses on fixed track systems [28][33][34] or to rigid pneumatic tyres [10][12][35] and just a few experimental studies [8][14][36] to removable tracks fitted on top of wheels. The most significant difference between these cases are the spacing between the track shoes and the slip between the wheel carcass and the tyre as well as between the tyre and the track. Also, since most of the tracked vehicles are designed for military use, the data is not easily accessible. The automobile industry has also studied tyre-ground contact. Although the wheel dynamics are determined quite precisely, the models normally assume the ground to be relatively smooth and hard. [10][12][37]

Most of the calculation models related to the area seem to be empirical or experimental. Equations have been constructed to certain terrain condition and machinery, and they rarely can be regarded as universally reliable. The models contain a lot of uncertainties and assumptions, so they should be used only as a reference. In prior research, the surface pressure is defined without acknowledging the soil characteristics. Assumptions are made about the contacting surface between the track and the ground, and hence about the pressure distribution.

The surfaces of the wheels and the track are not flat, and the surface pressure is normally calculated for a planar surface. Even the wheel pattern can cause the local surface pressure to peak. The local peak surface pressures are critical when studying the bearing capacity of the forest ground. If the track produces a larger force than the shear strength of the ground, the surface of the ground gets torn and the bearing capacity decreases. The equations for calculating the surface pressure of the bogie track vary greatly. They often contain variables and constants that have been defined in experimental studies. The effective surface area of the track in soft terrain is only an estimation if the deflection of the tyres or the shape of the track are unknown.

One of the most popular ways to describe the machine-soil contact is mean maximum pressure (*MMP*). The term is used in literature in various occasions [30][38][39][40] and has many different variations for different situations. It must be mentioned that normally the pressure model covers only a specific application in certain conditions, so the models might not give consistent results when used to calculate the pressure in a different application. Normally the *MMP* model do not take terrain behavior into account, thus soil compaction or dislocation is neglected.

In 1972, Rowland formed a Mean Maximum Pressure (*MMP*) model [38] for link and belt track on rigid road wheels:

$$MMP_{rigid} = \frac{1.26W}{2n_r \times A_l \times B\sqrt{t_t \times d}} \tag{2.1}$$

Rowland also developed a model for belt track on pneumatic tyre road wheels:

$$MMP_{pneumatic} = \frac{0.5W}{2n_r \times B\sqrt{\delta \times d}} \tag{2.2}$$

Based on the Rowland model, Littleton & Hetherington constructed their own *MMP* model in 1987 [39]:

$$MMP = \frac{W}{2n_{axle} \times B \times L} \tag{2.3}$$

Equations do not take the terrain conditions into account. The empirical equations give valid or accurate solutions only if the terrain conditions are similar than in the initial measurements and the basic structure and dimensions of the machine is the same. Along with the development of the machinery, the equations formed decades ago have become more and more inaccurate. They still can give an approximate magnitude for surface pressure if comparing different machines in similar terrain conditions.

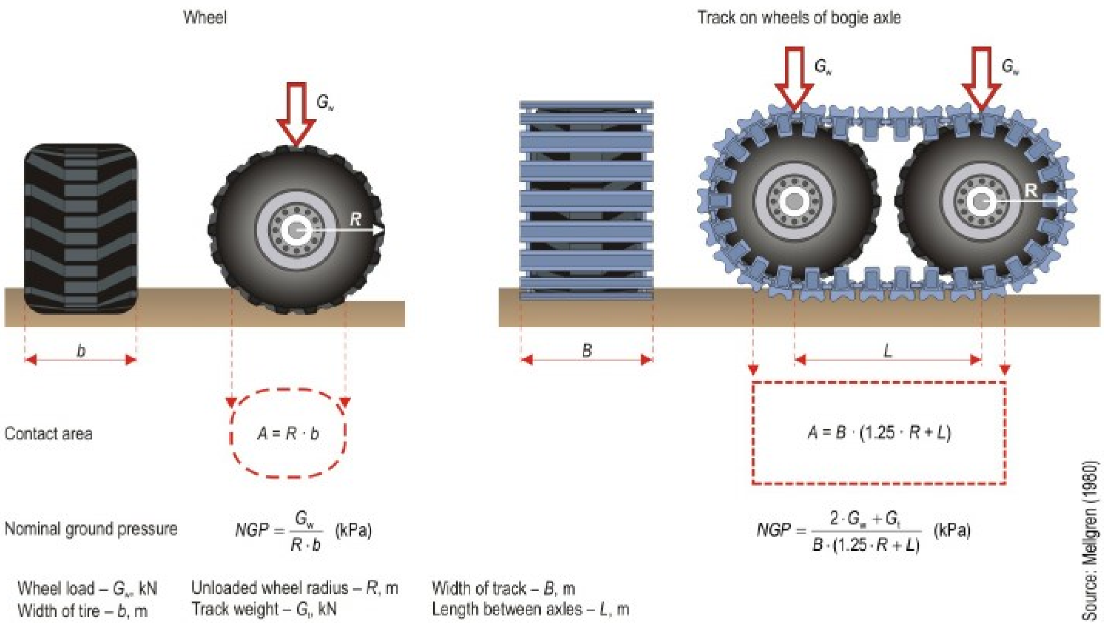


Figure 9. *Calculation of Nominal Ground Pressure* [41]

Also, other commonly used pressure models have been developed. Nominal ground pressure, *NGP*, recommended by Mikkonen and Wuolijoki 1975 [42] is commonly used in the Nordic countries to determine the pressure under the different size tyres with a track or bogie track of a forest machine.

$$p_{NPGtrack} = \frac{W}{(0.72r_1+0.53r_2+l_{AX})\times B} \tag{2.4}$$

$$p_{NGPbogie} = \frac{W}{(1.25r+L)\times B} \tag{2.5}$$

The pressure calculation presented in Figure 9 is roughly the same for the track, but it takes also the weight of the track into account. The surface area is the mean theoretical area with which the tyre or the track is in contact to the ground.

Ground pressure index, *GPI*, was constructed by Dwyer in 1984 [43]:

$$p = \frac{W}{B\times d} \times \sqrt{\frac{h}{\delta} \times \left(1 + \frac{B}{2d}\right)} \tag{2.6}$$

Ground pressure index is an indicator that is based on WES-method that is a semi-empirical method to studies the soil penetration resistance and thus evaluates the vehicle trafficability and can be for example used to compare different tyre models. The WES-method was constructed in Waterways Experiment Station by the US Army in 1960's.

The equations of Ziesak & Matthies (2001) [44] for ground pressure index based on Maclaurin's limiting cone index model [45] is comparable to Dwyer's ground pressure index.

$$p_{GPI} = \frac{W}{B^{0.8}\times d^{0.8}\times \delta^{0.4}} \tag{2.7}$$

The NGP and GPI model give an estimation of the trafficability of the machine, they normally give too small values compared to other equations [31], and they should only be used as a guideline in situation, when there is a risk of getting stuck or forming unbearable ruts in a single pass. Most of the surface pressure model shown don't consider the soil apart from the sinkage. Empirical sinkage models are normally constructed in specific terrain condition and rarely can be applied in other situations. When utilizing the equations, the soil and terrain properties they have been defined in, must be checked. The results may vary, if the properties differ from the original conditions.

In 1982 Wong et al. constructed a modified load–sinkage relationship for muskeg prior to the failure of the surface mat. It may be rewritten to describe the general pressure–sinkage relationship for any loading area, including a circular one [46]:

$$p = k \times z_0 + \frac{m_m \times {z_0}^2 \times L}{A} = k \times z_0 + \frac{4m_m \times {z_0}^2}{D_h} \tag{2.8}$$

The values for k and m_m can be derived from a measured pressure-sinkage curve using the least squares method.

In 2008, Ishigami et al. [47] proposed an alteration to Reece's equation [48] that accounted for the semi-elliptical distribution of stresses beneath the wheel arc length:

$$p(\theta) = \left[ck'_c + \gamma bk'_\varphi\right] \left(\frac{z}{b}\right)^n (\cos\theta - \cos\theta_s)^n, \tag{2.9}$$

where θ is a variable wheel angle and θ_s is the static wheel-soil contact angle. This alteration resulted in a necessary distinction between the shape of stress distributions beneath loaded plate and wheel sections.

VTT, the Technical Research Centre of Finland Ltd has constructed a surface pressure calculator for forestry machines [32]. The calculator is based on Winkler's elastic soil model [49], which assumes the soil to resist the machine weight by acting like springs that are compressed. The calculator utilizes a simple empirical soil–wheel-interaction model. The solution is iterated from an elastically linear soil model. The result is only simplified representation of the real-life situation, because the model neglects any unlinearities in the soil and it assumes the terrain to be horizontal and even. Also, the machine model is simplified.

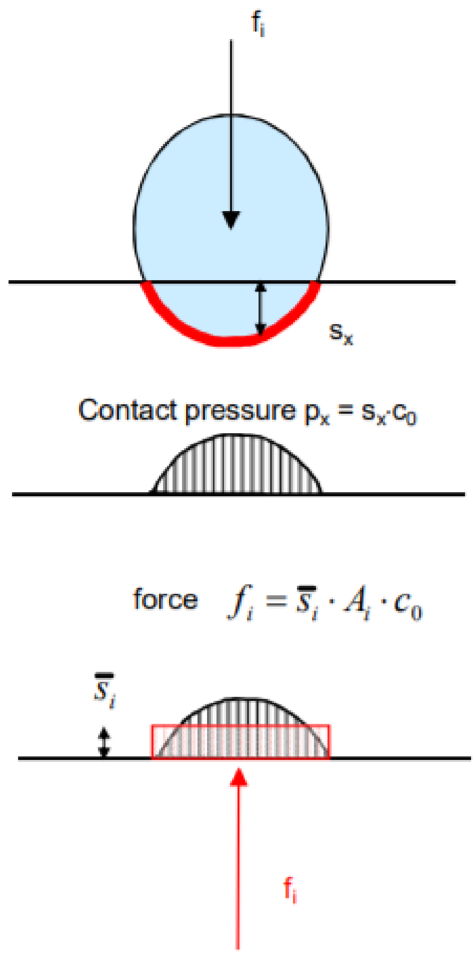


Figure 10. *Pressure distribution and force under a single tyre* [32]

Figure 10 introduces the basic principle of the model. The contact pressure and resisting force can be calculated based on the sinkage, contact area and soil cohesion factor. The Winkler model [49] assumes, that the soil is cohesive.

2.3 Pressure distribution under the track

The pressure seems to be unevenly distributed under the track. The peak values for the pressure seem to be under the tyres and the shear stress is at its high in front of the track, where the track shoes take first contact to the soil, because to shear stress and shear displacement is largest there. The thrust for the driveline affects the slip between the track and the soil surface. Wong's research [34][50][51] of tracked vehicles is mostly based on the traditional structure of a tracked vehicle. Although the structure is different in the application this thesis mainly concentrates into, the results seen in Figure 13 can give a good estimate how the pressure is distributed under the track. Wong's models also acknowledge the varying physical properties of different soil types. According to Wong, it seems, that the softer the soil is, the more evenly the pressure is distributed.

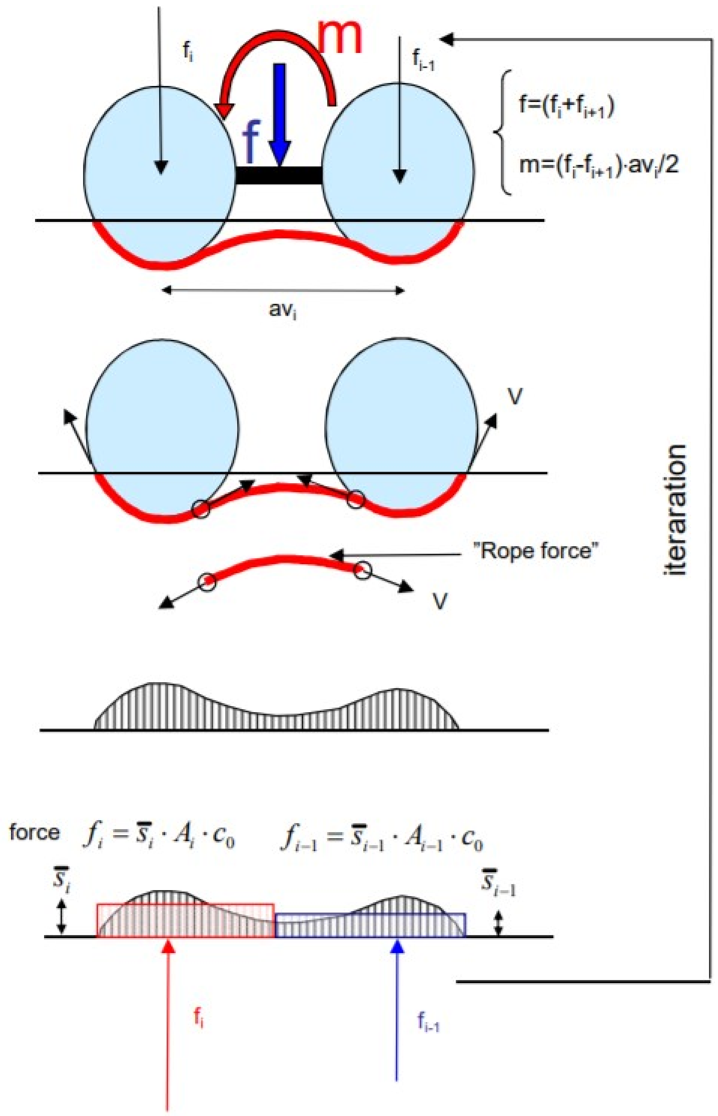


Figure 11. *Pressure distribution and force under double tyres with track* [32]

The pressure distribution can be found with a highly iterative process. The spring forces are iterated until the error is acceptable. The calculations consider the bearing capacity of the flexible part of the track that is between the tyres. Most of the pressure models assume the track to be a rigid structure or oversimplify the model to get results. If constructing a model for the track dynamics, it can be based on a simple geometry for the track cross members. The track plates are attached together with links. Because additional link track doesn't have support rollers between the wheels, the stress distribution can be modelled with a simplified rope model. [32] The track is assumed to stay on a straight path on top of the tyres so the forces due to track misalignment can be neglected. Slip occurs between the wheel carcass and the tyre as well as between the tyre and the track and it is possible to occur between the soil and the track. The tyre inflation pressure and the elasticity of the tyre determine the transformation of the tyre. In simulations, these phenomena are normally neglected. The shape and thus the contact area with the ground increases with the increase of rolling speed [10]. The driving speed for a forestry machine in soft condition is so low, that the tyre deformation due to speed is insignificant.

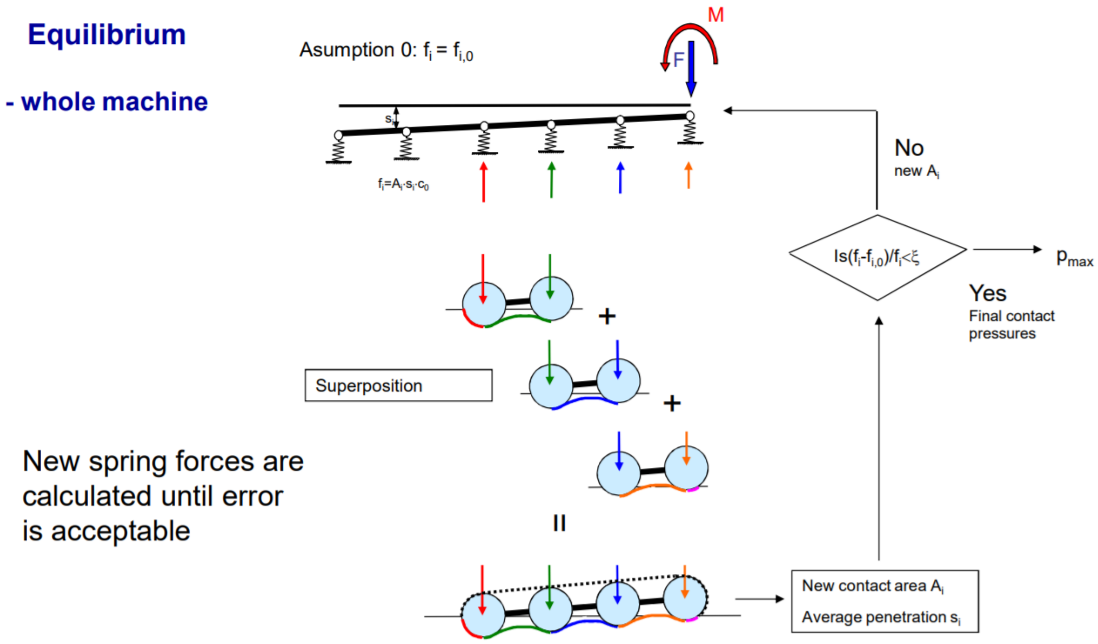


Figure 12. *The equilibrium of the whole machine* [32]

When observing a traditional track system, the pressure distribution differs from a tyre-track system, mainly because of the elasticity of the tyres and the distance between the wheel hubs. Also, the track tension affects the effective surface area under the track system. A conventional track system is composed of metal tracks, tensioners and pulley wheels. Conventional track systems are utilized in the forestry, but they normally demand the machine to be constructed with a fixed track or be fitted with a bogie that has the track system and thus no tyres. When using a conventional track system, if the machine is required to be equipped with tyres, the whole bogie must be changed. Track use is prohibited in some areas, so a fixed track system can lead to problems when moving the machine between sites. Due to the problems caused by highly fatiguing metal tracks, also rubber-tracked undercarriage for heavy agricultural vehicles have been developed [52].

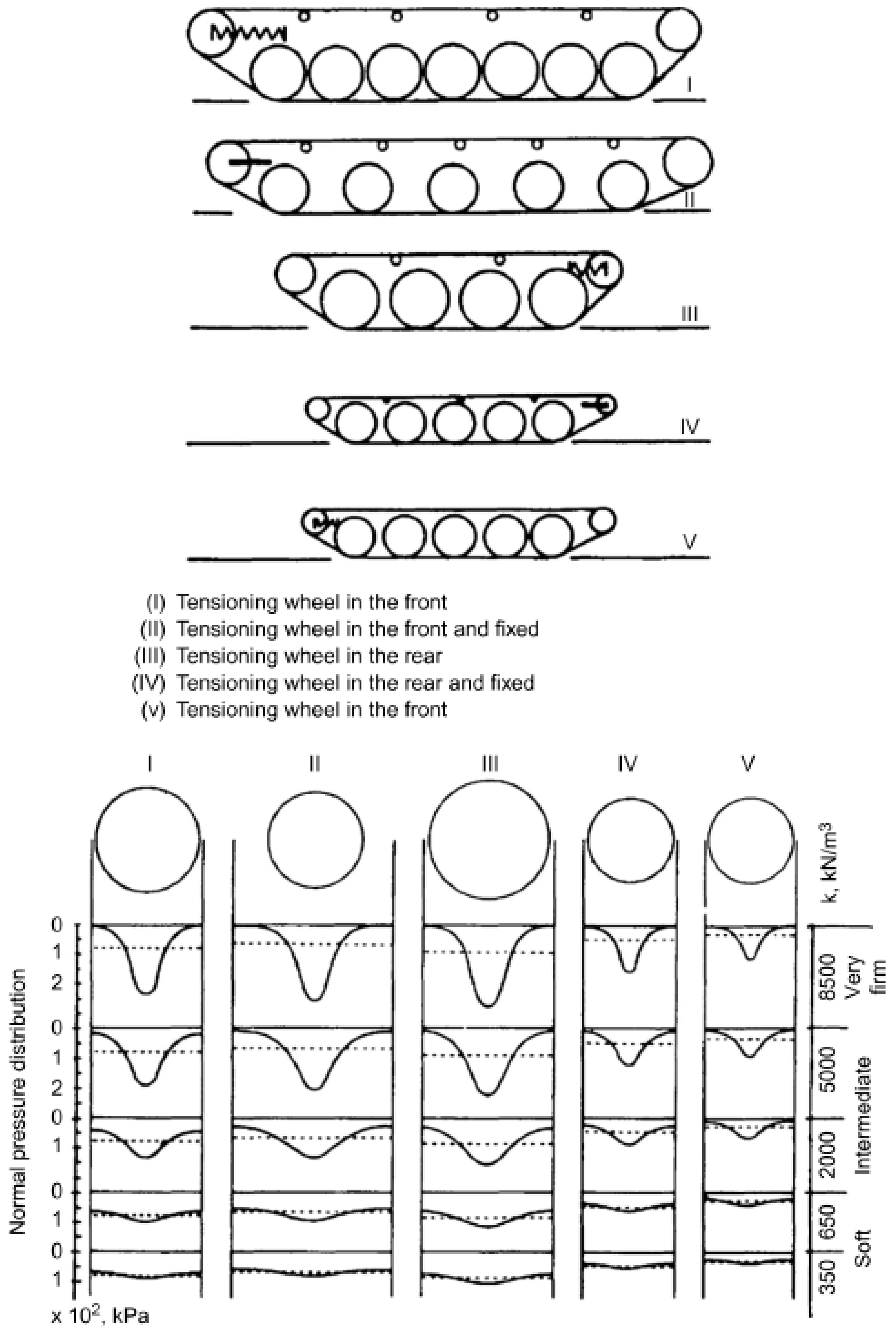


Figure 13. *Static normal pressure distribution under various track systems over terrains with different stiffnesses* [51]

Figure 13 proposes that the pressure distribution varies according to the firmness of the soil. Wong claims [51], that the pressure under the rollers or tyres and the firmer the soil is, the sharper the pressure peak is. Soil compaction spreads the load on a larger area, because the effective surface area increases. Also, the distance between the wheels and the number of the impacts the pressure distribution and magnitude. Wong’s assertion is supported by civil engineering sources. According to the civil engineering, different soils have a different pressure distribution under the load [53][54]. The tyre inflation pressure seems to have no influence on the pressure distribution under the tyre in soft wet soil, only the axle load has. [55]

Although, the conventional track system eliminates the slip caused by the tyres and the spring effect the tyres have, the noise level of the system is greater than for the tyre-track combination. A track-track system also absorbs the vibration due to the elasticity of the tyres. Also, the gear ratio changes due to wear of the machine and track elements. The track tension is normally adjusted with a tensioner wheel, but if the wear is extensive, the tension must be restored by reducing the track elements.

2.4 Load-sinkage correlation

The sinkage is the maximum sinkage under the load. Normally the soil has at least partial elastic recovery, thus the final rut formed after the machine is smaller than the sinkage. The sinkage depends on the compaction of the soil. Load-sinkage test are normally conducted with a test plate and the force (weight) is applied perpendicularly to the surface. When considering a tire/track-soil contact, the strain is not perpendicular to the soil surface, because of the movement of the machine. The movement produces more shear force to the soil and failure may occur with lower surface pressures than expected. The critical sinkage is the sinkage where the surface mat is broken.

From Bekker's equations the soil sinkage can also be calculated [56]:

$$z = \left(\frac{p}{\frac{k_c}{B}+k_\varphi}\right)^{\frac{1}{n}} \tag{2.10}$$

In 2011, based on the Bekker model, Meirion-Griffith proposed an equation that takes the soil type into account [35]:

$$z = \frac{3W}{b(3-\hat{n})\hat{k}d^{\hat{m}+0.5}}^{\frac{2}{2\hat{n}+1}} \tag{2.11}$$

Table 4 lists the soil specific variables the Meirion-Griffith model uses.

Table 4. *Proposed model soil properties, based on Meirion-Griffith* [35]

	Dry sand	Calcium silicate	Moist earth
$\hat{k}$ (kN/mṅ+ṁ+2)	1604	16.7	78.8
$\hat{n}$	0.8	0.48	0.88
$\hat{m}$	0.39	0.00	-0.49

Taghavifar and Mardani proposed an equation for sinkage in 2014 [57]:

$$z = \frac{19 \times {W_{wheel}}^2}{10} + \frac{7 \times W_{wheel}}{20} - (21 \times V) - \frac{7 \times N^2}{2} + (23 \times N) + 16.74, \tag{2.12}$$

The Taghavifar and Mardani model is highly empirical, so it should be used carefully. Taghavifar and Mardani have neclegted the units in their calculations. Because of the different nature of the sinkage equations, they have not been futher studied in this thesis.

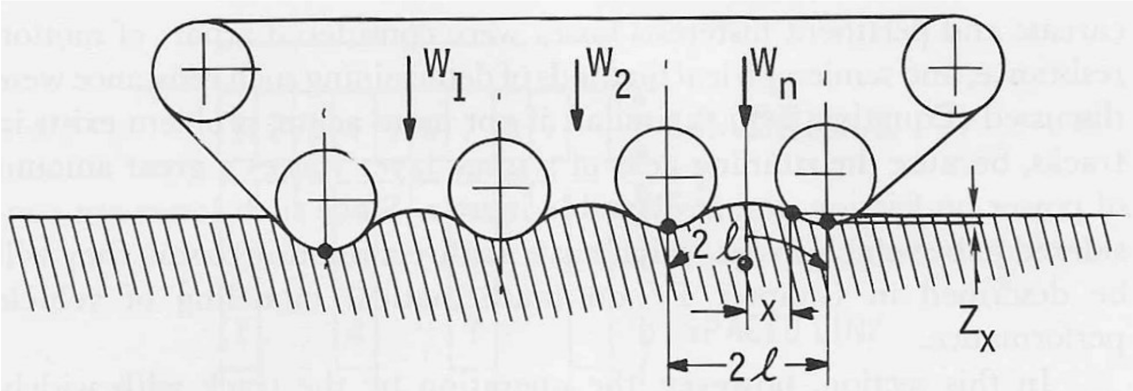


Figure 14. *"Static" sinkage distribution under the catenaries of a flexible track. Road wheels are assumed to be very small.* [58]

All the equations are formed to a specific type of soil. Because different soil types behave differently when load is applied to them, only the applicable equations should be used when evaluating the bearing capacity of a harvesting site and choosing the suitable machinery for the harvesting operations. Like in Figure 14, most of the calculations take only the static loading situation into account, because modelling the dynamics of the vehicle requires a high level of mathematical knowledge.

2.5 Engineering properties of soil

The simulation models can be based on several terramechanical theories. When construction a soil model, the basic structure of the material has to be defined. When simulating terrain behavior, the soil properties must be defined accordingly. Some soil types are easier to define, because their consistency is more homogenous, and they compose of granular particles that have little variation in size or the soil can be represented as a continuum, which has specific characteristics. The soil can be defined as an elastic medium, a plastic medium or a rigid equilibrium depending on the characteristics of the soil. Simulation models contain always assumptions and simplifications, but in some cases can give realistic results about the soil behavior. In this case, the strength, cohesive and frictional properties of the soil must be well known.

If the soil is considered to be a continuous material, the shear strength, spring stiffness, damping modulus, and friction modulus etc. of the soil can be defined. If the soil is considered to be an elastic medium, the theory related to the subject is widely accessible. If the soil is modelled as an elastic material and the pressure is not large enough to cause failure to the material, soil compaction can't be modelled. An elastic model is a simplified presentation of reality, because the particle structure of the soil is not considered.

Cohesionless soil in composed of visually detectable particles. The properties of the soil are based on the interaction between the granular particles, mostly the friction. Particles have a compaction coefficient and there can also be space between them. The shear strength, if it can be even considered to have it, is based on the friction, because the particles don't have physical bonds between them.

In simulation models, a strongly simplified material represented the soil. The soil model can be thought as non-linear material, because the shear and compaction are not linearly related to the load. [59] If soil material is simulated, certain material properties have to be defined. These properties can be, but not limited to the following:

- Young's modulus
- Bulk density
- Particle size, if applicable
- Permeability
- Water content
- Porosity / air content
- Organic matter content
- Plastic modulus
- Elastic modulus
- Poisson's ratio
- Shear modulus
- Shear strength
- Tensile strength
- Tensile yield stress
- Tensile ultimate stress
- Compressive ultimate stress
- Coefficient of thermal expansion

Table 5. *Other material characteristics needed for a simulation model*

Material characteristic	Method
Symmetry	isotropic / orthotropic / transversely isotropic
Stress-strain response	linear /hyperelastic / elastoplastic
Failure criterion	None / Modified Mohr / Maximum shear stress (Tresca) / Distortion energy (von Mises)
Fatigue	None / Unified material law (UML)

Table 5 defines other material characteristics that describe the behavior of a simulated material. Normally localized sinking and slip failure have to be ignored, because of the complexity of their modeling. Because the porosity and fibers of the soil, some soil types can't be modelled with the software available, so physical properties have to be chosen the way that the behavior of the simulation soil is as similar as possible with natural soil. Porous soil is more prone to compaction, because the air and the liquid drains from the pores once the pressure increases. Soil compaction modeling is highly dependent on the properties the soil particles or continuum material have been given. Hard and incompressible particles normally just reorganize their selves and the compaction results from the decrease of the spaces between the particles. Some soil types contain lots of pores so the space between the particles is filled with air, water etc. When compacted, the pores empty out and the soil gets compacted. If the load is large enough, the deformation can be permanent.

Peat soil is unsuitable or problematic soil to construct roads or buildings onto. Due to the fibrous consistency and high organic content of peat, it has also proven challenging to model and simulate. Peat soil is normally highly porous and thus can contain large amounts of water and air. Peat is problematic, because it can hold up its dry weight in water. The physical properties change according to the water content of the peat soil. Also, the amount of organic matter in peat soil alters the bearing capacity of the soil, since the roots of plants and trees make the soil more resistant. The organic matter content of peat can be significantly high, up to 99 %. [17][18]

Peatland can also be considered as a layered soil type. Although peat deposits can be quite deep, the soil rarely has the same consistency on a wide area in the forest. The tree density affects greatly the characteristics of the soil. Peatlands generally have a high level of moisture if not drained, and the wetness of the soil affects the bearing capacity of the soil. [60] Saarilahti has carried out thorough research of classification of peatlands [24]. According to Saarilahti, when classifying a peat soil site, nearly 70 different variables can be identified. This makes the construction of an accurate model for the simulation rather challenging. Peatland can be described according to tree cover, humification degree, brightness temperature, index of trafficability, vane shear strength etc.

3. SOFT SOIL MACHINERY CHARACTERISTICS

Soft soil forest machines must be able to operate in challenging conditions. Low surface pressure can be a key feature for a soft soil machine, thus the soil gets less ruts and is less affected by the logging operations. Surface pressure is normally lowered by increasing the surface area of the machine that is in contact with the ground. Soft soil machines usually have a similar basic structure that is formed with the objective to optimize the machine surface area and to minimize the surface pressure and rut formation.

From the literature, some machine design parameters tend to recur. Because the main structure of CTL forwarder of all the noteworthy machine manufacturers is similar, the design parameters, which can be altered in the currently established design, can be listed. Normally the machine is equipped with a bogie with tyres and the track is installed on top of the tyres. A fixed or a permanently fitted track system is ignored in this thesis, because its limited usage and rareness in CTL products. The bogie dimensions or structure can be altered, and bogie balancing can be adjusted.

3.1 Dimensions of soft soil machinery

The width of the machine must be as small as possible in thinning sites where the strip roads must be narrow. The size limitations for the machines are based on the either the legislation, when it comes to transporting the machine to the site, or to the dimensions of the site itself. There must be enough space between the remaining trees or other terrain characteristics. The machine width can’t be increased because of the limitations in the transport of the machinery. For example, the Finnish road traffic law sets limit a to the width and the weight of the machine that can be transported in a certain kind of truck and skid/trailer combination. According to the Finnish legislation, if the width of the machine increases to over 3.50 meters and the overall transportation length exceeds 30 meters, a safety car is needed. [61] The size criteria vary among different countries. The dimensions of the vehicle transportation trucks are normally stated in national legislations and they vary even inside of the European Union. Use of additional safety and warning equipment and machinery always increases cost and effort put in the transportation. Similar limitations can be found in every business region, although the limiting values vary. The basic problem with transportability is the same.

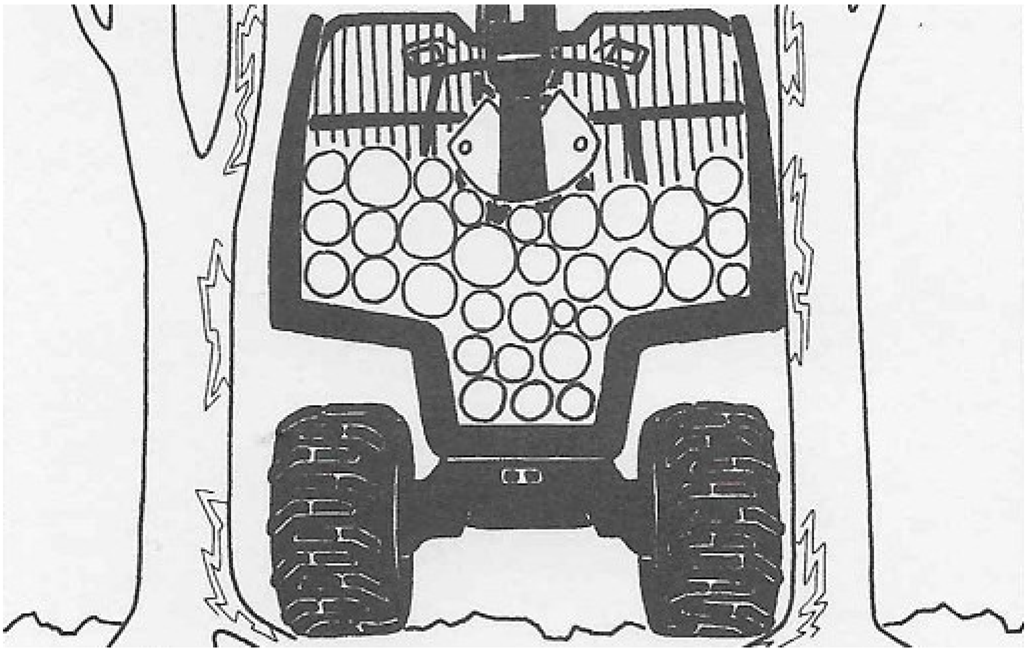


Figure 15. *Too narrow strip road increase the danger of stem and root damage.* [3]

The limitation for the machine width varies according to the national legislation. The driving feature in addition to the limitations regarding the transportation of the machine, is the width of operating trail that the forestry machine leaves behind in the forest. The maximum operating trail width is normally determined in national legislation or directives for forestry operations. The trail width that the machine lefts behind is based on the width of the machine. The operating trail should be as narrow as possible, especially in thinning sites, so the residual forest will be disturbed as little as possible. The ruts the timber harvesting machinery left behind are also wider if the track is wider.

The machine weight is also an issue to be addressed. When the weight increases, the machine generates a greater strain to the ground if the weight/contact area ratio doesn't remain the same. Advanced material development can decrease the density of the material; thus, the machine becomes lighter, but the other physical properties of the material remain the same or are improved. If the material used for the component is lighter than but as functional as the previous material used, the machine weight can be decreased. When the machine gets lighter, the axle load will decrease also. Thus, the surface pressure will be lower, if the dimensions of the machine remain the same. The weight of the machine is a crucial factor when considering the impact, the machine has to the terrain. Although the machine weight is not always linearly related to the rut the machine forms, it is one of the determining factors when it comes to the trail the machine leaves behind.

This thesis mainly focuses on the dynamics of the rear carriage of a forwarder, because the largest forces occurs under it. As the forwarder is loaded, the weight of the machine is mainly centered in the rear part of the machine. Thus, the wheel loads are greater on the rear carriage. Even if the rear is heavier than the front of the machine, in normal operating conditions the rear follows the same path as the front carriage and the rut the front carriage causes are re-strained by the rear carriage. The machine size must be optimized. Machines with larger load spaces can carry more timber in a single pass, but the weight increases when the machine and the load space are larger. This may lead to unacceptable terrain damage. Smaller machines are more agile and less harmful for the environment, but because their smaller carrying capacity, they tend to be less productive. [1]

Some basic variables impact the dynamics of the machine. The dynamics of the machine change when the track starts rotating. A stationary machine can be compared to a building foundation made from partly flexible material. The friction coefficient between the soil and the track as well as between the track and the tyres affect the forces applied to the soil. The tractive force from the driveline is conducted to the soil-track interface and it produces the machine movement. Resisting forces are caused by friction, deformations, elasticity of additional material or obstacles on the machine path.

3.2 Dynamics and the geometry of the bogie

The dimensions of the bogie affect the contact area of the machine has with the ground. The distance between the wheel hubs determines, together with the tyre size, the contact area. In theory, surface pressure be lowered with extending the bogie, but it is uncertain, if a conventional driveline, tyres and tracks will withstand the change in the geometry.

The damage to the terrain when the machine turns increases when turning angle is tight or the contacting surface is large. Although increasing the track's contact area with the ground decreases the surface pressure that influences the soil, a larger contact area inflicts greater strain to the ground surface, when the machine turns. Bekker proposes in *Theory of land locomotion: the mechanics of vehicle mobility* that the ratio of the contact length of the track and the width of the tracks (distance between the track centers) (=length/width) should not be larger than 1.7 or 1.9 for the vehicle to stay controllable. [62]

The location of the driveshaft affects the distribution of the load [63].

$$\frac{\text{bogie front wheel load}}{\text{bogie load}} = \frac{F_e}{G} = \left(\frac{1}{2} - \frac{y+r}{L} \times tan(\alpha)\right) - (\mu + sin(\alpha)) \times \left(\frac{y+r}{L} - \frac{r}{i \times L}\right) \tag{3.1}$$

where

$$\mu = \frac{F}{G} = \frac{\text{bogie tractive force}}{\text{bogie load}} \tag{3.2}$$

Equation 3.1 assumes the bogie to travel parallel to the slope and to stay that way regardless of conditions the machine is used in.

The distribution of load between the front and the back wheel of the bogie with equations 3.1 and 3.2. The bogie can also be balanced with hydraulic actuators. The aim of the balancing system is to ease the obstacle crossing and smoothen the drive. Hydraulic actuated bogie balancing the load distribution under the track can level out the load between the tyres. Basically, the contact area of the track can be increased by increasing the distance between the wheel hubs. Thus, the track will be longer and more prone to breakage. The portion of the track between the tyres forms an arch. The shape of the arch depends on the tension of the track and the axle load.

The surface pressure is strongly linked to the distribution of the load on the bogie and the tractive force. Normal pressure under the track varies; It is at its highest under the wheels and decreases between the wheel hubs if the track belt is loose enough**.** The bogie has a tendency of lifting the front wheels when driving forward. This means, that the axle machine load is unevenly distributed between the wheels.

3.3 Track dimensions and tension

The track tension is one of the challenging variables on model. A realistic, working cycle tension level is hard to define, because it is influenced by the tyre elasticity, the stretch of the track components and the basic mounting tension of the track. Tracks normally loosen up after a while since first mounting and must be tighten. The suitable tension in not an exact value, because of the lack of a tensioning system. The tension can be chosen according to the flexible of the tyres, the friction coefficient between the track and the tyres, the terrain conditions, the transformation in the track elements after running-in, among other things. The friction coefficient between the rubber and the steel track is estimated to be 0.7. The friction coefficient for peat soil – steel track (smooth steel) contact is estimated to be 0.39 [64].

The track tension also influences the magnitude of the slip occurring between the track and the tyres. Even if the track seems to be tight mounted on top of the tyres, due to material yield, the tension varies when driving on varying terrain condition. If the track runs over an obstacle (e.g. a rock), the tension of the track is momentarily much larger than in common operating conditions. If the track is flexible, it can lengthen under pressure. A track is usually partly flexible: the track shoes are rigid, but they are connected to each other with links that can rotate. If the track can be modeled with a flexible route between the tyres, the pressure should be realistically distributed.

The spacing of the track shoes affects the pressure under the track. The area with contact with the soil is one of the determining factors when it comes the surface pressure and the pressure distribution under the vehicle. Although increasing the surface area of the track decreases the surface pressure linearly, spacing between the track elements is needed to enable the excess material to exit the track. If loose material piles up between the track and the tyres, it may result in over-tighten and eventually drivetrain or other kind of machine failure.

When observing the surface pressure of the forestry machine track, the shape of the track shoes has only little effect when the soil surface is soft. The studs that normally are welded to the tack to increase traction can break the soil surface and thus assist the soil compaction. Without the studs, the machine control can be challenging. Especially in soft soil, the soil can get pressed away under the tracks causing irreversible ruts. The shape of the cross member can influence the dislocation of the soil if the track is slipping extensively. If the soil can’t escape under the track shoe, it will not be heavily dislocated, and the ruts are formed only because of the compaction.

3.4 Auxiliary wheel

To improve the flotation of the machine in soft terrain, additional idler or an auxiliary wheel can be mounted between the bogie wheels. It transforms the machine towards a traditional tracked device, although the durability of the additional idler wheel has not been proven at this point. The auxiliary wheel increases the contact area between the tracks and the tyres and thus helps to even out the pressure peaks under the tyres. The idler wheel or wheels must be able to move vertically because of the rough terrain the machines are utilized in and the must be able to support load without adding too much strain to the track or the ground.

Figure 16. *PONSSE 10w is available with a fixed additional axle for the PONSSE Wisent forwarder and with a hydraulic-operated additional axle for the PONSSE Elk ja PONSSE Buffalo model.* [65]

Some forest machine manufactures have been adding an additional idler or an auxiliary between, in front of or behind the bogie wheels to even out the pressure distribution under the track. The auxiliary wheel can have its own axle or a separate mechanism. An example of a commercial product can be seen in Figure 16, where auxiliary when is mounted to a separate axle. The European Commission is funding projects that study the utilization of a third wheel between the main rear wheels, but the final reports aren't available yet [21].

The mechanisms normally have on flexible or adaptive design to adjust the pressure, force or the position of the wheel. The structure must be lightweight and needs to have a decent load-bearing capacity to prevent wheel malfunction or mechanism breakdown in fluctuating terrain conditions. In all the solutions, the wheel must be able to follow the surface of the ground to prevent the mechanism to fail due to over-loading the cylinder. The cylinder can have a constant pressure or force, but it has to follow the environment flexibly. This requires complex control of the flow rate to the cylinder. Due to the novelty of the design, any wheel malfunctions or function breakdowns are not fully documented or the magnitude of the bearing capacity of the wheel proven.

Also, other solutions for increasing the surface area of the machine have been developed. Because the width of the machine rarely can be further increased, an extra wheel can also be mounted behind the load space. The wheel can carry some of the weight produced by the loaded timber, but the weight of the structure itself is added up to the total weight of the machine. The contact area of the structure with the ground must be large enough to decrease the overall surface pressure. Lengthening the machine can also complicate the movements of the machine, especially when turning. Because the auxiliary wheel has a different trajectory than the bogie wheels, it compacts the trail on a different are than rest of the wheels. It may decrease rut formation or at least even out the difference between the trails inflicted by the tracks.

4. EFFECT OF MACHINE LOAD TO THE SOIL

When determining a soil material, it is normally highly simplified, so that some effects the machine load has to the material, can be compared. The machine load and dynamics impact the soil in various ways. If the soil is considered to be as any material, the main variables that describe the effect of machine load to the soil are von-Mises equivalent stress, shear strength and maximum shear strength in the soil material. Different loading conditions cause the soil material to behave differently. A static load causes less shear stress, but the load impacts the same spot for a longer time [57][66][67].

4.1 Soil deformation, stress and strain

Soil deformation is a significant part of evaluating machine's environmental impact. As any material, soil behaves in a predefined, but complex, way under loading. When the soil is loaded to the level of plastic deformation leads to permanent deformation and thus ruts. The deformation is a result of soil stress caused by the machine weight and movement. When the soil is loaded, the loading forces inflict stress to the soil. Strain is deformation related stress. Soil deformation and stresses are normally a study area of civil engineering.

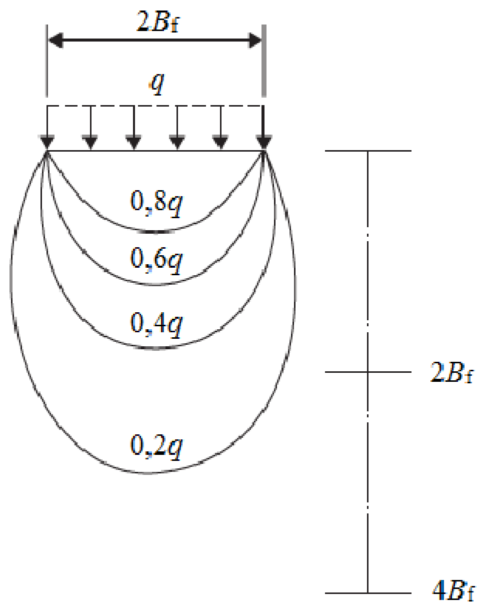


Figure 17. *Stress bulb in soil under the foundation* [68]

The stress the machine produces to the soil is an important factor when studying the effect forestry has to the environment. Figure 17 illustrates the pressure bulb under a static foundation. Modelling the effect of a dynamic machine has not been achieved in the same level yet. Information about internal pressure in the soil is an important factor when comparing effects different machines have to the soil. The surface pressure can be determined in the upper surface of the soil. The pressure that affects deeper in the soil affects the properties of the soil even after the machine has passed by.

4.2 Rut formation

The maximum soil compaction is also influenced by the loading time and the displacement of the soil particles. These are some of the determining factors, when studying rut formation. A high surface pressure normally indicates formation of unwanted ruts. Rut formation is a result of many different machine and soil related factors. The shear stress under the machine seems to be a driving feature, when considering rut formation. When the tyres roll faster, the velocity of the machine is larger and the contact time with a given point in the soil is thus shorter. This reduces the soil compaction, because the loading time is shorter. [14][57][66][67] The effect of a longer bogie should decrease the rut depth, because the surface pressure decreases. If the wheel hub distance is increased, the soil would be under loading a longer time, although the load would be smaller. An auxiliary wheel is added to even out the pressure peaks under the track, so the maximum surface pressure should lower.

Predicting rut formation is challenging. The soil type must be precisely defined, and the calculated values only apply to homogenous soil types. Rut formation is a combination of a large number of variables. Soil properties, such as moisture content, stiffness, chemical composition, shear strength and method deformation, define how the soil behaves under load. The effect on soil moisture content is explained in subchapter 5.4. In general, a high moisture content seems to deepen the ruts. Machine characteristics, such as weight and track surface area, are also important. The operation situation has a significant role, when predicting the depth of the ruts the machine lefts behind. Site planning should be done the way that the strip roads don’t cross the most sensitive spots and turns are kept minimal. The machine operator should monitor the driving speed and the size of the load to minimize the impact to the soil. Soil compaction can also be reduced with slash reinforcement to strip roads [69].

Not many applicable equations for rut formation exist. Rut depth according to VTT, the Technical Research Centre of Finland Ltd [32]:

$$\mathrm{Rut}_{\mathrm{i,N}} = \sum_{\mathrm{j}}\left[0.001008 * \mathrm{e}^{\mathrm{p}*\ln(\mathrm{i,j})*5.4362}\right] * 0.5 * (\mathrm{N}^{1.28} + 1) * \left(\frac{\mathrm{c}}{10000\ \mathrm{Pa}}\right)^{0.3} \quad (4.1)$$

The first component of the equation represents the drive rut, the second the drive number effect and the last is a normalization against the strength.

For wheeled tracks:

$$\mathrm{Rut}_{\mathrm{i,N,track}} = 1.6 * [(\mathrm{N} - 1)^{0.4} + 1] * \mathrm{Rut}_{\mathrm{i,N}} \quad (4.2)$$

where the first component of the equation is an empirical correction.

VVT's equation form the rut depth according to the surface pressure and the number of passes. The also the soil cohesion into account. Still, these equations are highly empirical. The effects of different machine configurations have been studied, but reliable equations for rut formation have not been widely found yet. [14][70]

5. ANALYSIS OF DESIGN PARAMETERS

The design parameters that were chosen to this thesis are bogie dimensions (especially the distance between wheel hubs), the usage of an auxiliary wheel, bogie balancing and peat moisture content. All of these are known to have an effect to the behavior of the machine in peatland forestry.

5.1 Bogie dimensions

The magnitude of the pressure depends on the axle load as well as the contact area of the track. The bogie dimensions can be altered by increasing the distance between the wheel hubs. Increasing the distance between the wheel hubs should increase the track contact area between the wheels and thus lower the surface pressure. However, the total increase in the surface are is dependent on the tension of the track and which kind of arc it forms between the wheels. The equations developed to describe surface pressure under a bogie track don’t the durability of the structure into account. The tyres are elastic and the track elements yield, especially when new. If these uncertainties are neglected, a wider set of track and longer bogie would result in a much lower surface pressure. However, the track width cannot be increased much due to small clearance between the track and the frame and load space.

Larger tyres would even out the distribution of the machine load on the track, because the contact area increases. Increasing the size on the tyres leads to the same problems as increasing the dimensions of the tracks. A larger diameter shortens the distance between the tyre and the load space and the bogie doesn’t have the space to rotate. Even though the tyres rarely are wider than the track, some bogie structure may be designed the way the clearance between the bogie and tyres is quite small. The tyre offset can’t be increased indefinitely, because the overall machine and the trail it lefts behind will widen. Even though the surface increased significantly, the surface pressure isn’t reduced in half if a large tyre is replaced with a bogie track [63].

5.2 Auxiliary wheel

Studies from the effect of an idler wheel mounted between the main wheel hubs is not widely accessible yet. CTL manufactures have developed different kinds of structures to mount an extra wheel to the normally two-tyred bogie. The basic idea is the increase the surface area between the track and the tyres. Because the tyre diameter can’t be increased much, because of the spatial limitations, an auxiliary wheel increases the effective surface area.

The auxiliary wheel is supposed to even out the pressure distribution under the track. Without the auxiliary wheel, the pressure is mainly distributed under the main wheels and the track carries some of the weight. Adding an auxiliary wheel that is pushed against the track with a constant or altering force, decreases the pressure under the main wheels. The structure of the auxiliary wheel system increases the weight of the machine, so the efficiency of the system must be good enough to the weight gain to be discarded.

5.3 Bogie balancing

The bogie balancing can be studied with uneven forces between the front and rear wheel. The idea of the bogie balancing system is to even out the effect of the topography to the dynamics of the machine. The weight of the machine is unevenly distributed between the wheels, but the surface pressure equations normally consider the machine weight to be evenly distributed between all wheels.

The bogie has the tendency to lift the front wheels when driven forward. The tractive force and the friction between the ground and the track or the tyre inflict a force that forces the front of the bogie to rise. The effect of the tilt of the bogie is minimized by the bogie balancing system. The balancing system also prevents the bogie to make sudden movements, so the stability of the machine remains adequate and thus the driving comfort convenient. Soft soil machines can be equipped with a bogie, that adjusts its angle according to the terrain. The front of the bogie tries to rise, when the machine is driven forward. The front wheel lifting tendency is a result of dynamics of the bogie traction. The angle the machine touches the ground, influences also the pressure distribution, because of the center of gravity changes. The soil is strain differently depending on the soil-track contact angle. The bogie balancing affects the angle the bogie meets the ground. Thus, the cutting angle with the soil surface alters according to the bogie angle. The bogie balancing may worsen the situation in sites with poor bearability, because the machine weight is unevenly distributed to tracks. This may increase rutting. [63]

The effect of the track rotation is sometimes neglected to simplify the simulation model. Yet, the torque of the tractive force may alter the result more than predicted. The balancing system can be modeled as an effective force difference between the front and rear wheels. The difference in effective forces is realistic, but when the torque is neglected from the simulations, the bogie loses its tendency to tilt backward when driving forward. If the dynamics of the tilting bogie is ignored, the surface pressure peak don't occur, and the effect of rutting may be significantly lower than in reality.

5.4 Peat moisture content

From previous studies [18][71][72][73], it is known that peat soil has certain characteristics in certain moisture levels and the assumptions can be utilized in a simulation model. Soil wetness affects also the bulk density of the soil [60]. The moisture content is really complicated to be fully modelled, because it would demand detailed modelling of soil pores, their compaction under loading and the fluid dynamics of the water leaving the pores.

The surface pressure distribution under the track seems to be more even when the soil is softer. The stiffer the soil is, the smaller the peaks of the surface pressure are. [51] Pure peat is extremely porous and fibrous, so it can be considered to be soft, because of its high compressibility. Because of the softness, in addition to the complexity of the consistency of peat, developing a realistic soil model to peat soil has proven to be a challenge that requires extensive research. The moisture content of the soil affects its bearing capacity. The soil strength decreases with the increase of the water content. Porous soil can absorb a large amount of water. Cohesive soils can retain a lot of water and its strength is strong dependent on the surface pressure of the capillary water. [27][26] The soil water potential affects the soil strength by altering the effective stress. According to Towner in 1961 [74], the shear strength of unsaturated soil is:

$$S = C' + (\sigma - \chi\psi)\, tan\, \theta_f \tag{5.1}$$

Soil moisture seems to have a great influence on the compaction. The soil moisture content determines the maximum value achievable of soil's bulk density. For each soil type and compactive effort there is a particular value of water content, known as the optimum water content at which a maximum value of bulk density is obtained. [27] If the soil moisture increases, the compaction seems to increase, according to Shahgholi and Abuali [66] when testing silt soil in 2015. Similar results have been reported by McNabb et al in 2001 [60] and by Mosaddeghi et al. in 2000 [72].

5.5 Comparison of the theoretical models

The comparison of the different models if not unambiguous nor simple. The equations contain different variables, some of which cannot be determined in the following field tests. The correlation of different variables varies in the models. An effort was made to gain consistency in variable naming within this thesis regardless which the original author has named the variables. The calculations are based on values found in prior research and literature. The detailed calculations are presented in appendix A. The calculations are made with an imaginary machine and its dimensions are chosen according to existing machines. The selected variables are listed in Table 6.

Table 6. *Predefined variables, chosen according to previous studies and existing machines*

variable name	variable	magnitude	unit
rigid area of link track cleat in proportion to the whole track area	A_l	0.6	-
tyre width	b	0.710	m
track width	B	1.00	m
tyre diameter	d	1.340	
tyre carcass height	h	0.20	m
distance between wheel hubs	L	1.50	m
number of axles	n_{axle}	2	-
number of wheel stations in a track	n_r	2	-
unloaded tyre radius	r	0.67	m

Table 7. *Comparison of different mathematical models of surface pressure and their significant variables*

equation (number)	equation	variables (machine weight not included)
2.1	MMP, link or belt tracks on rigid road wheels	number of axles, the effective area of the track, tyre diameter
2.2	MMP, belt track on pneumatic tyre road wheels	number of axles, the area of the track, tyre diameter, tyre deflection
2.3	Littleton & Hetherington MMP model	number of axles, area of the track
2.5	NGP, bogie track	size of the tyres, area of the track
2.6	GPI	number of axles, the area of the track, tyre diameter, tyre deflection, tyre carcass height
2.7	GPI, Ziesak & Matthies	track width, tyre diameter, tyre deflection

The variables, that have an effect to the outcome of the surface pressure equations, are listed in Table 7. All the equations are based on the weight of the machine, but the other variables vary. The area of the track is the most commonly used variable. Because some of the equations list the number of axles or road wheel to have an effect to the surface pressure, adding an auxiliary wheel seems to decrease the surface pressure and thus improve the flotation of the vehicle. Increasing the distance between the wheel hubs increases the track area, so lengthening the bogie seems to be a solution for decreasing surface pressure.

Equations 2.8 and 2.9 are not included in the comparison, because of their different nature and the lack of consistent and available measuring data needed for the equations. For future studies, if the soil properties can be measured, the equations take also the soil properties into account. Equation 2.4 gives the same results as 2.5, if the tyres are the same size. The equations chosen don’t take the bogie balancing nor the soil properties into account.

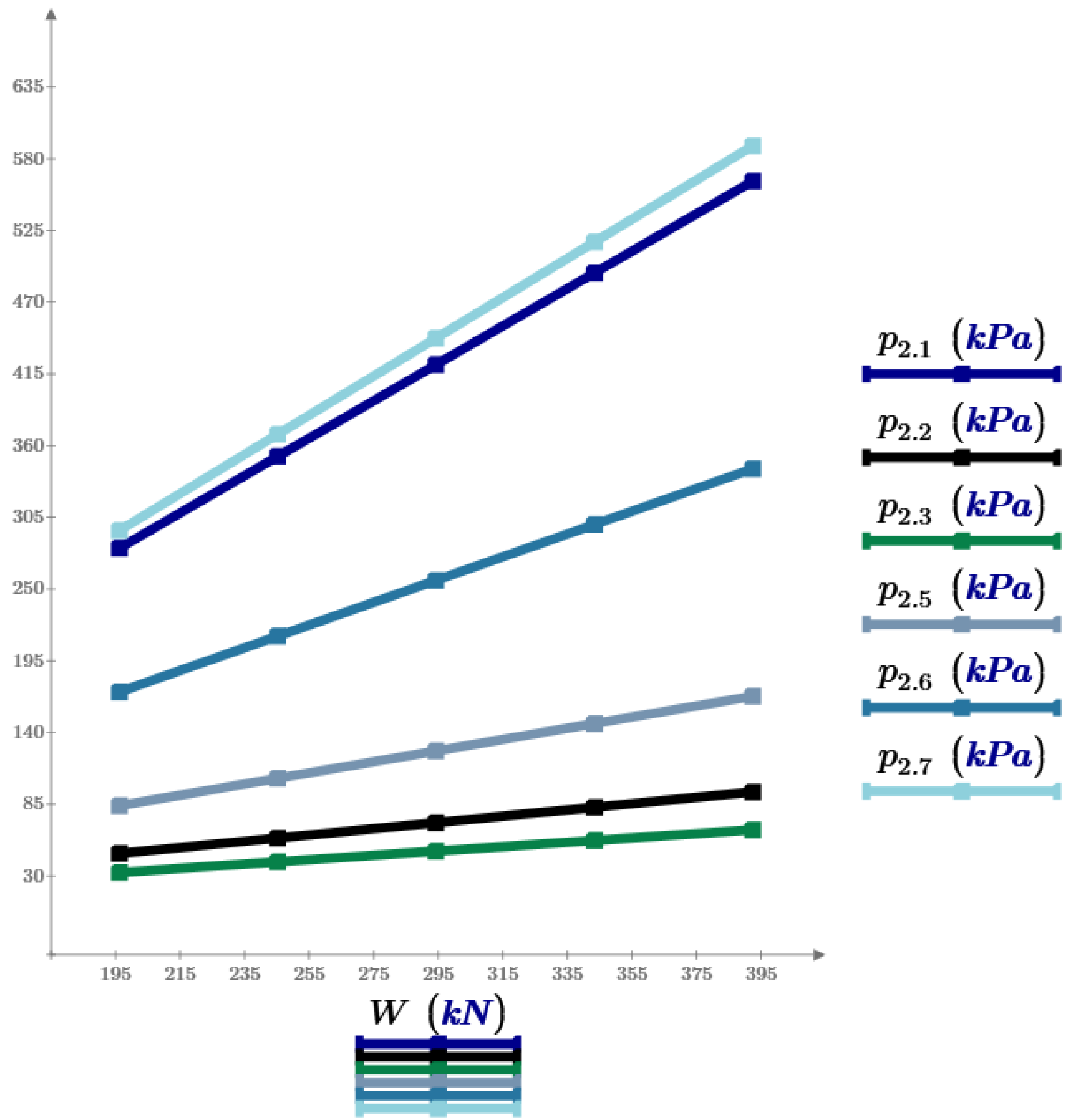


Figure 18. *Results from the calculations. Detailed calculations in appendix A.*

Comparing the different models has proven to be challenging. Models use many different variables and the rarely are linearly related to each other. Figure 18 summarizes the surface pressure values from equations from subchapter 2.2. Pressures linearly dependent on the machine weight. Equations are not fully comparable, but they give an estimate of the surface pressure that the machine produces to the soil. When comparing different sites, it is crucial to use the same equation, if applicable, so the pressure calculations are equally calculated.

If available, the surface pressure should be calculated or simulated only with equations that are formed to represent a certain soil type. Peat soil is rarely homogeneous, and the surface layer may be more delicate than the lower layers. This stratified structure of the soil makes the calculation more and more complex. Simulating soil types with low bearing capacity introduces also challenges with modelling the compaction and recovery after the loading situation. Reoccurring loads are normally modelled with highly empirical equations that are based on non-repeatable test results.

5.6 Possibilities of computer simulation

The simulation model can represent the rear carriage of the machine or the whole machine. The tension generated by the boom movement can be neglected or the situation, when the boom causes most torque to the frame, can be chosen. There is a risk of oversimplifying the model. The bogie tilting, and track rotation are complicated features if modeled realistically. The center of gravity is normally considered to be in the center of the bogie and the axle loads are only assumptions based on a typical machine in a certain load-bearing range.

Simulating soil and terrain behavior have proven to be challenging. Some soil types are easier to model than others. Granular material, i.e. coarse sand, is relatively straightforward to model, if the size and the size distribution of the grains can be determined. Soil that is non-homogeneous is more complex the model. An aim to future studies could be to study the behavior of the machine in peat soil. Because the literature is not in agreement with the physical properties of peat soil and the natural conditions vary greatly [24][19][18], the soil must be simplified if simulated. A simplified material can represent peatland, although it won’t behave completely realistically. The fibrous consistency needs a unique material model to be constructed. Modelling the soil has proven to be challenging. A combined model of the wheel and the track must be constructed. Some simplifications are normally done. Modelling the slip between the track shoes and the rubber tyre had proven to be too challenging and is ignored in this thesis. It might have an effect in the magnitude of the shear force applied to the peat by the track shoes. The bogie-track –contact, the tyre-track contact is often neglected.

Also, the slip between the track and the tyres as well as between the tracks and the ground is a major challenge in a simulation model. The pressure and sinkage equations introduced in chapters 2 and 3 are highly iterative and tend to oversimplify the behavior of the machine. Some of the equations don’t take the soil composition into account and the results can be thus misleading. The soil type affects the magnitude of the shear force that causes the soil surface to break. The slip causes the ground surface layer to shear and thus decreases the bearing capacity of the soil. It is expected that the terrain damage encountered in the complete machine testing are much greater than in the simulations and the small-scale testing, because of the slip. The failure in the soil surface results in the exposes the lower soil layers to the mechanical wear inflicted by the machine and thus the sinkage increases.

Modelling the entire machine can be too challenging and laborious, but at least the bogie, tyres and track should be modeled. The structure should be simplified due to the capacity of the simulation computer. A simplified model enables more accurate comparison of the effects of selected design variables. To the results to be comparable to a real-life situation, the simulation model should take into account the whole machine. In the case of a traditional CTL forwarder, the wheels of the front carrier cross the measuring point before the rear carriage, and the soil in that spot is loaded and strained twice.

The tyres can be modeled as a solid, if the focus is to study the pressure distribution under the track and a realistic tyre model would be too laborious to construct. Although the tyre is modeled as a solid, the material of the tyre should be chosen to be soft enough so that the tyre is able to deform under pressure. A pneumatics tyre would deflect depending on the inflation pressure. The tyre deflection of deformation increases the contact area with the track. A conventional track system has been already modeled in several applications. With a functional simulation model, realistic effects on the soil can be studied. Figure 19 shows the distribution of the shear placement under a conventional track system.

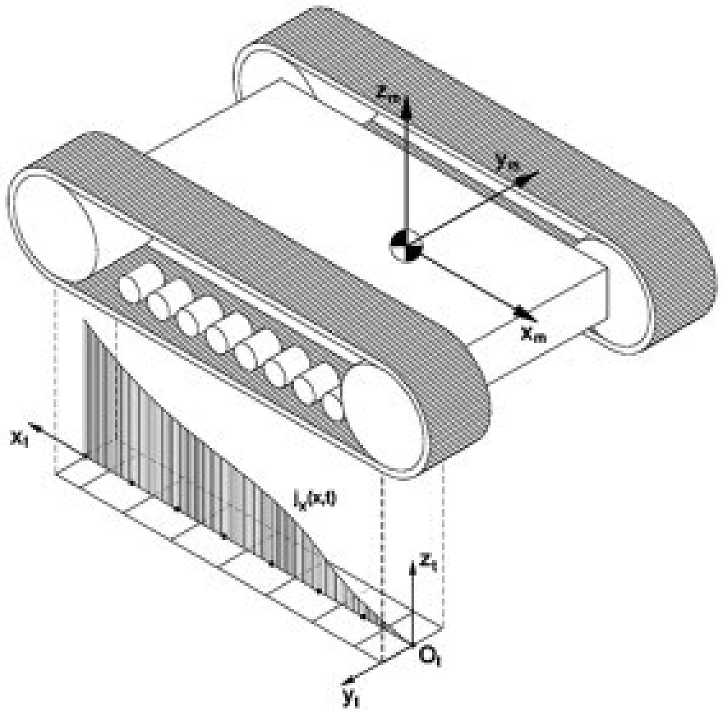


Figure 19. *Illustration of longitudinal shear displacement developed at the track–terrain interface.* [28]

Computational modelling of soil is normally done by assuming the soil to be either a continuum of material or separate particles. Discrete Element Method (DEM) can be used, if the soil can be considered to consist of particles, whose physical properties can be defined. If the soil in considered as a cohesive material in the simulation, the simulation model can be constructed with Finite Element Method (FEM) software.

Simulation are primarily conducted with simple geometry and elementary design, if the initial goal is to study to effect of the size of the surface area, not the shape. By changing the shape of the track shoe cross-section, more contact area can be created. A slightly curved design helps also to gain traction in challenging terrains. The most significant challenges are faced when modeling the dynamics of the tyre-track-soil interaction. The elasticity of the components must be considered. Also, the tension of the track varies the shape of the contact area. A loose track tends to hang loosely between the tyres on top of the bogie and the slip between the tyres and the track increases. Modeling unrealistically these phenomena might cause significant errors in the results.

Most of the theory and calculations assumed that the contact was a tyre-ground contact, and the properties of the soil were repeatedly neglected. The theory related to construction and foundation engineering are constructed for stationary structures. So, neither they can be directly compared to other models. Most of the equations introduced in subchapter 2.2 are constructed for silt or clay soil. When studying typical boreal forest soil, the results can be different because of the consistency of the soil. Especially when considering peat soil, the compaction and softness of the soil evens out the pressure distribution under the track, as Wong states in *Terramechanics and Off-Road Vehicle Engineering: Terrain Behavior, Off-Road Vehicle Performance and Design* in 2009 [51].

Before creating a simulation model, the results that are wanted as a result of the simulation have to be defined. If the simulation situation is poorly defined, the results are not reliable. The soil type affects the behavior of the soil, so the simulation model has to be constructed accordingly so the soil compaction is realistic. The behavior of the soil, the track itself and the tyres, all affect the surface pressure of the track. Simulating a greatly complex system, such as a dynamic machine, requires large calculation resources, and because of the complexity, the model has a lot of uncertainties.

6. FIELD TESTING FOR SURFACE PRESSURE

Because of the lack on reliable surface pressure or rutting equations, filed testing is still the most significant way to validate the design of the forestry machines. Small-scale tests give more information about the properties of different soil types and complete machine tests give results about the real behavior of the machine in logging sites.

6.1 Small-scale testing

The aim of the small-scale study is to define the sinkage and shear strength in peat soil in different pressures. Although the small-scale test does not realistically describe the forces the track applies to the ground, it can give a relation between the surface pressure, sinkage and shear strength. The slip can be neglected, because only the vertical force was applied. In reality, the track slip produces a shearing force to the top layer of the soil in front of the track. A bevameter is a device with which soil properties can be measured. A basic design for a bevameter is shown in Figure 20.

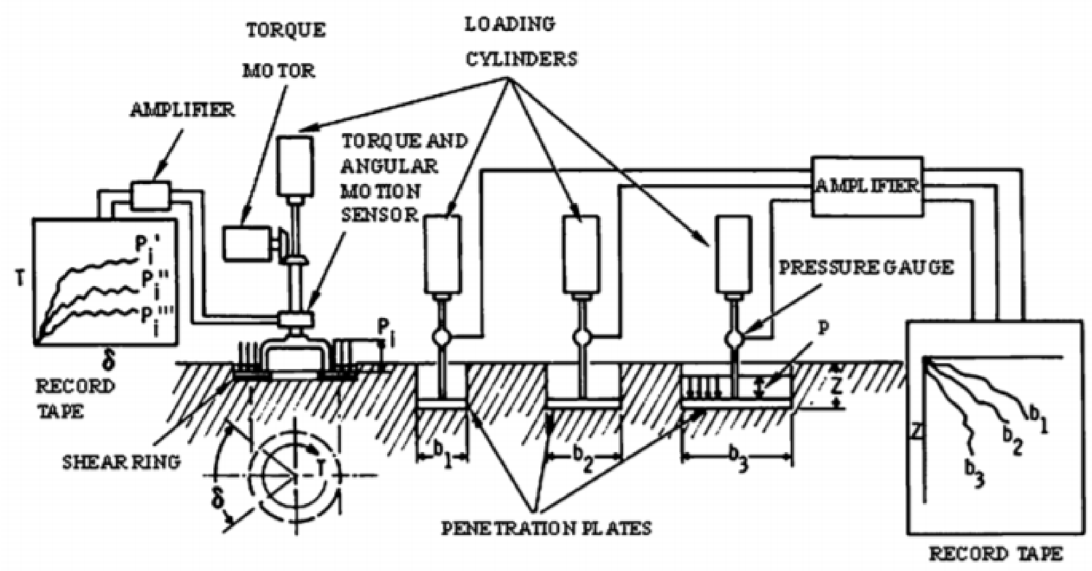


Figure 20. *Schematic view of a bevameter type instrument.* [62]

For a beneficial test, the process must be described in full detail. The area of the tested surface and the testing load are the most significant measures to be documented from the test bench. Also, the soil properties must be known, if when testing sinkage. It should be able to standardize the measuring conditions, so the results are consistent and comparable. The rut depth measurement method should also be thoroughly documented, and the outcome unambiguously represented.

The results can be helpful if constructing a more realistic simulation model, when the soil properties can more precisely defined. Small scale testing is normally used to define the characteristic of the soil and they rarely give comparable results to actual situations. With small-scale testing, different track geometries or tyre patterns can be compared to each other. However, the dynamics of a rotational movement can be challenging to produce, if trying to validate a track design.

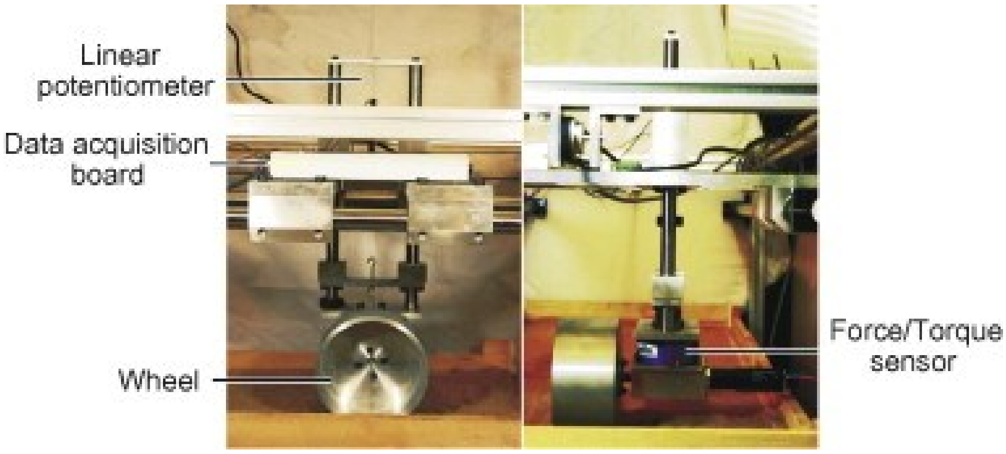


Figure 21. *Single-wheel vehicle-terrain testbed* [35]

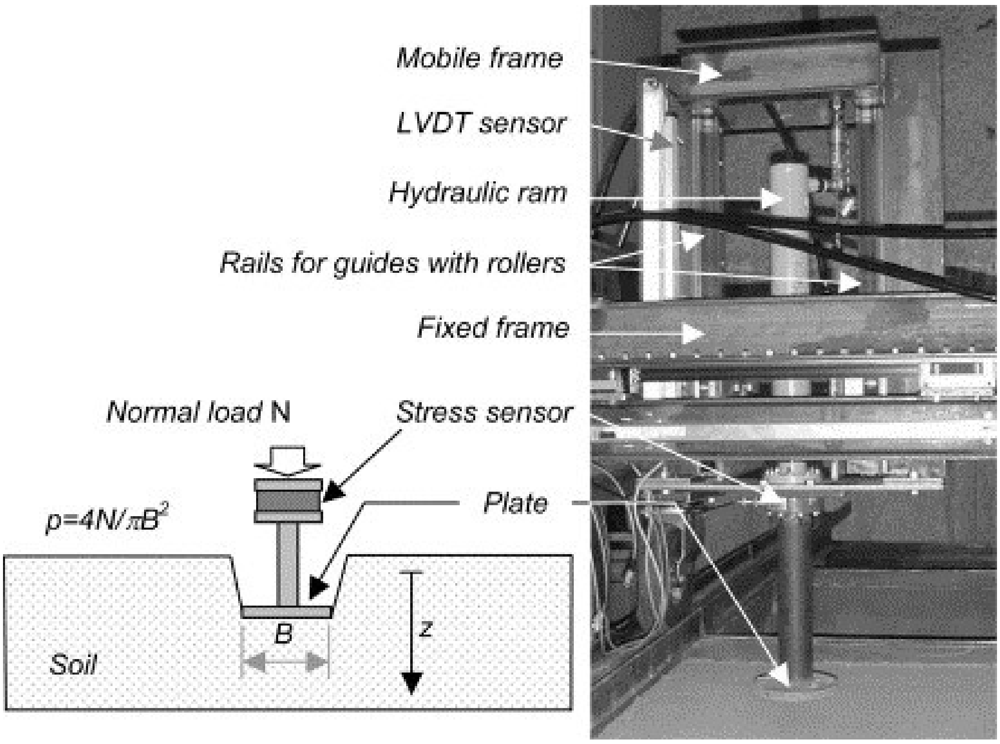


Figure 22. *Sinkage equipment of the experimental device* [75]

The instrumentation of a small-scale study is normally a test bench that represents movement of a single tyre or a track element. In small-scale tests, the amount of soil is rather small, and the test area can be fully even out, defined and measured. Figure 21 shows a simplified structure of a single wheel design. Figure 22 represents a single plate, that is pushed down.

6.2 Full-size machine testing

In the complete machine tests, the results are expected to vary from the simulated ones. The weight distribution of a real-life machine can differ from the simulation model. The models are also constructed with average values for machine dimensions and don’t necessarily represent any existing machine type. The most important machine characteristics must be measured and documented. The machine weight, the surface area of the track (including the sunken area) and equipment the machine has on, must be recorded to enable the comparability of different machine types. Also, the tyre size and inflation pressures and the track type, size and tension should be monitored.

Testing with an actual machine is a challenging set-up to measure, but the results represent the situation that would occur in the forest. The test site must be thoroughly documented, so the variation in test circumstances can be evaluated. In the small-scale testing and the simulation model, the soil is normally loaded only once. In the full-size testing, the machine drives over a predefined area, so the soil in the trail is loaded twice, when the front and the rear carriage both cross it. Thus, the rut formation is different, if compared to the earlier results. It must be checked that the equations and test results compared represent the same loading situations, so the results are comparable. Measuring pressure under the bogie tracks requires pressure sensor to be placed in the test route. If comparing the result to theory introduced earlier in this thesis, the type of the soil must be taken carefully into account, because the equations give valid results only when compared to the sites with similar soil properties.

The measurement of rut depth can be problematic. Soil is seldom homogenous and thus doesn’t compress evenly, so the rut depth should to be considered as a mean value in a predefined area. Conventional measuring methods are often purely mechanical and are strongly dependent on the way the operator uses the measuring equipment. The results are comparable only if the same measurement method is used in all the measurement. Figure 23 shows the most common way the measure mechanically the rut depth in a test site. Owing to the evolution of measuring technology, more and more information on rut formation is available. For example, Light Detection and Ranging (LiDAR) [76] or photogrammetry [77] can be utilized when studying rut depths. The soil compaction is not steady, so the rut depth is normally given as an average value.

Figure 23. *Rut depth measurement on the straight rutting test tracks.* [78]

The soil is also irregular material, only in the small-scale testing the area can be evened out and the soil consistency known precisely. Although the small-scale testing can provide reasonable results, it doesn't take the slip between the soil and the track into account. The calculations don't seem to acknowledge the possible slip between the tyre and the track either. Natural soil is heterogeneous and can't be fully defined. The inconsistencies in the composition of the soil are extremely challenging to model and are not uniform. A soil model is only a presentation of a small portion of real forest site. As mentioned earlier, peat soil can contain up to over 90 % [17][18] material and its physical properties are also highly dependent on the water content of the soil. Forest peat soil also problematic due to the variation in increased bearing capacity caused by plantation and tree roots. Because of the inconsistency of soil, the test area should be thoroughly documented.

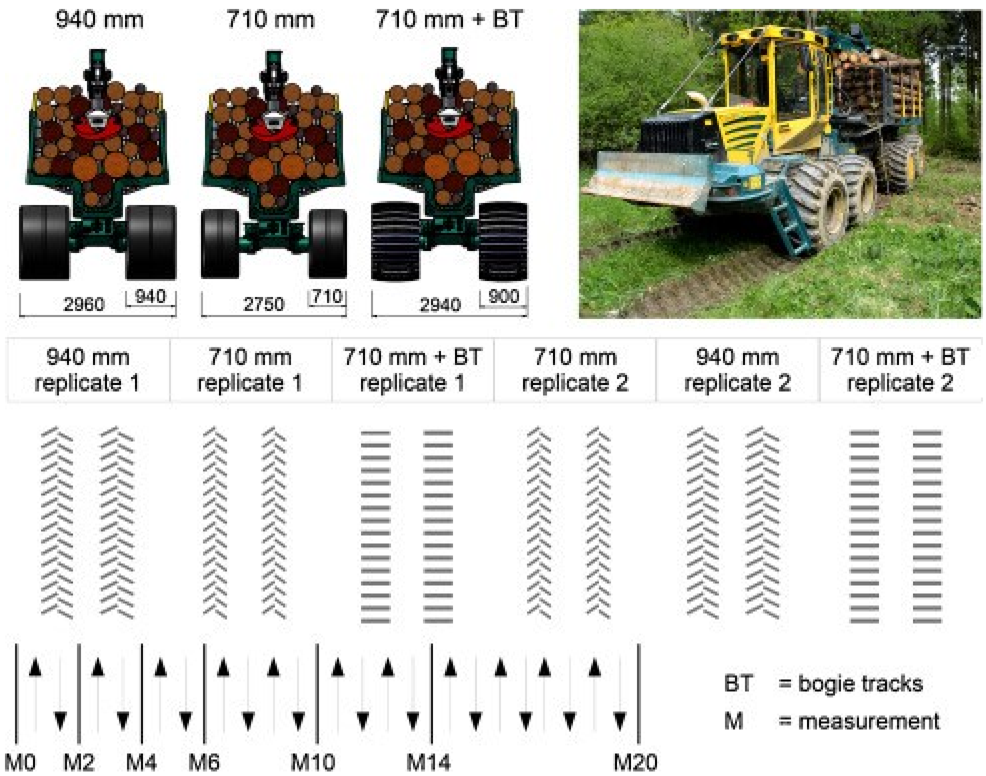


Figure 24. *Machine specifications and experimental design. Top left: machine dimensions (drawing: HSM Hohenloher Spezial-Maschinenbau GmbH), Top right: test machine (HSM 208f 11to). Bottom: experimental design and spatial arrangement of replicates.* [77]

The documentation of the test conditions is the key to valid results. If there are too many uncertainties, that are not documented clearly, the repeatability of the study deteriorates. Figure 24 gives an example of a full-size machine test. Repeatability is an important factor in reliable studies, therefore if testing multiple machine with different accessories or tracks, the machines must be similar in design and weight. Thus, the trail depth measurement results can be comparable. The machines must be the same weight and the tracks have to be defined or the same. The driving speed for every test run should be equal. The test area must be planned and documented carefully. Figure 25 shows a test site, where the rut formation is studied with a straight track, in the curves and in a curvy track. Some of the test tracks are only passed once and some of them multiple times to study the effect of the number on passes.

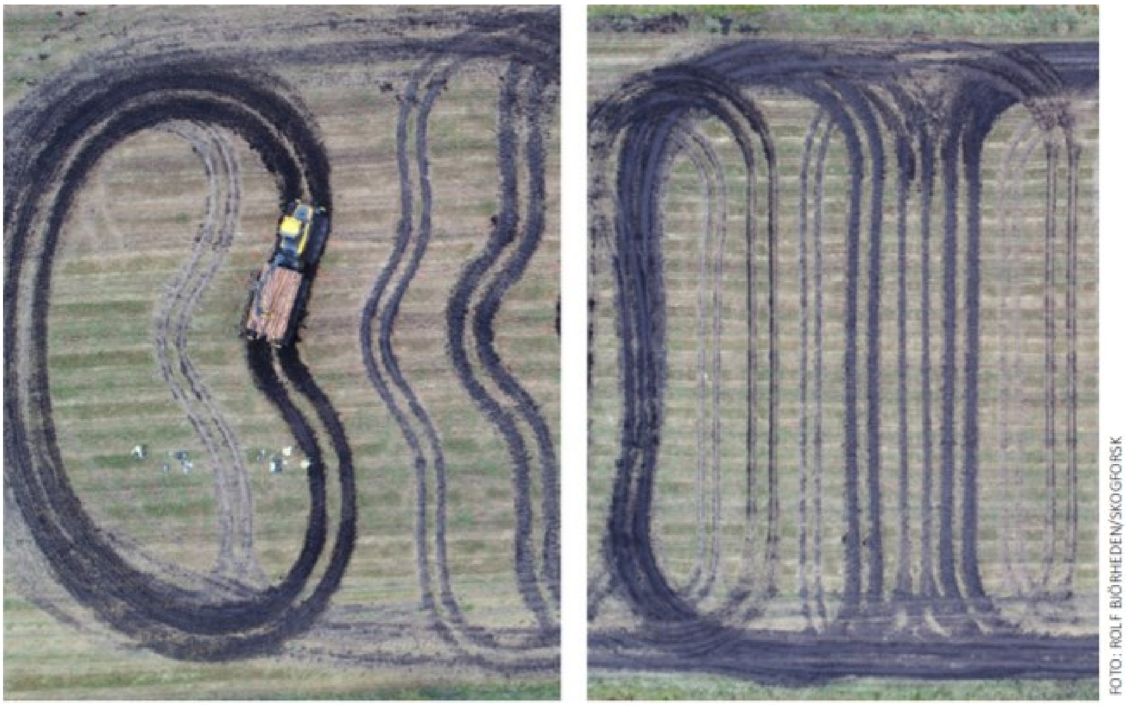


Figure 25. *Aerial view showing the layout of the 'slalom' (left) and straight (right) rut formation test tracks.* [78]

Complete machine tests are a way to validate the machine design. The lack of reliable calculation model forces the forestry machine manufacturers to carry out laborious field tests. Field tests give reliable results, when different machines are tested in the same time in the same conditions, but the tests normally contain a high number of variables, so their repeatability is poor. The test results still give a good estimate, when comparing different machine types based on their effect on the terrain.

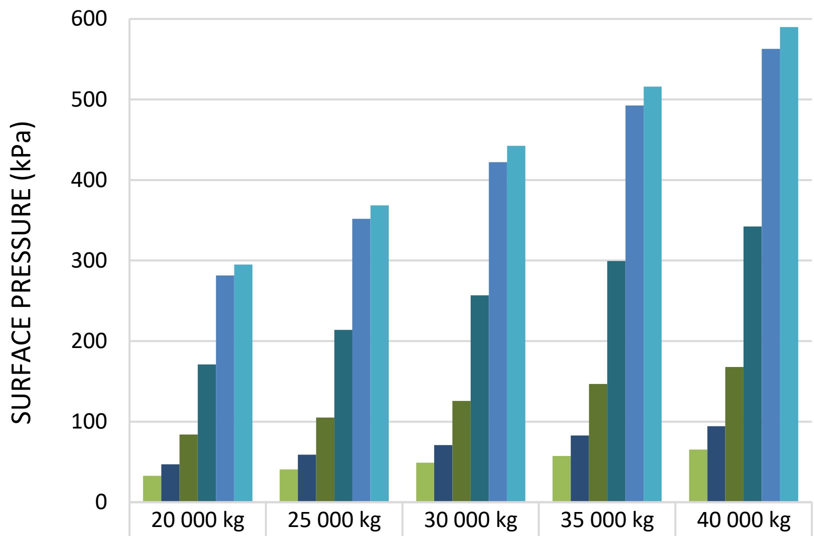
7. CONCLUSIONS

The driving feature to the soil surface pressure is the machine weight. The machine weight correlates with the surface pressure linearly. Using tracks, instead of plain pneumatic wheels in low-bearing sites, is an effective way to decrease the surface pressure and to protect the soil surface and thus minimize the environmental impact of mechanized timber harvesting. According to the results from previous studies and theory, the surface pressure decreases while the surface area increases. Widening the wheel hub distance increases the contact area with the soil and thus decreases the surface pressure.

If an auxiliary wheel is considered to an additional axle that can bare load, if divides the pressure more evenly under the machine and decreases the surface pressure [38][39]. The effect of a separate mechanism should be further studied. Bogie balancing evens out the differences in the surface pressure that are inflicted from unevenly distributed load. It may lead to problems in sensitive site because of the varying pressure distribution of the track.

The surface pressure can be calculated from the equations introduced in subchapter 2.2, although there will be some inconsistencies due to different soil properties used when defining the equations. As mentioned before, the pressure peaks in certain areas [51]. By designing the track shoe to be smooth-lined, some of the shear force peaks can be eliminated. Normally studs are welded the surface of the track to the machine to gain more traction. Studs can break the soil surface and thus decrease the strength of the soil. If the soil surface is sheared, the bearability decreases. [34][50][51] The moisture content also affects the shear strength of the soil and thus the bearing capacity. A high moisture content decreases the shear strength and thus the bearing capacity of the soil [27][60][66][72].

The differences with Wong's model [51] are partly related to the tensioning of the track. The track structure can also affect the results, because the slip between the wheel and the track as well as between the track and the soil surface can alter the distribution of the pressure. When the machine is stationary and the track tight enough, the results should not differ much.



	20 000 kg	25 000 kg	30 000 kg	35 000 kg	40 000 kg
MMP, Littleton & Hetherington	32,7	40,875	49,05	57,225	65,4
MMP, belt track on pneumatic tyre road wheels	47,256	59,07	70,884	82,698	94,512
NPI, bogie track	83,936	104,92	125,904	146,888	167,872
GPI	171,146	213,933	256,72	299,506	342,293
MMP, link or belt track on rigid road wheels	281,388	351,735	422,082	492,429	562,776
GPI, Ziesak & Matthies	294,94	368,678	442,413	516,149	589,884

Figure 26. *Surface pressure based on different models with variable machine weight. Detailed calculation in appendix A*

The magnitude of the stress on the soil surface when driving a machine equipped with only tyres is larger compared to the theoretical results with the tracked machine. All the tyre widths are replaced with the track width to better compare the models. Even though the values in Figure 26 are not fully comparable, they give an estimation for the surface pressure of a machine with a bogie track. The equations that give higher values for the pressure a normally constructed to rigid wheels, so the surface area is much smaller than for a tracked machine. The values given to a tracked vehicle may only be applicable in the conditions they have been constructed to, and that explains the variety in the magnitude of the results. The results vary much more than expected. A widely used maximum surface pressure for peatlands forestry operations is 50 kPa [24], and nearly all the calculations exceed that limit greatly when the total mass of the machine is more than 20 000 kg. The MMP model for rigid road wheel with a track and the Ziesak & Matthies model give considerable large values for the surface pressure, so they seem not to be applicable to this situation or poorly defined. If any of the variables is defined falsely, the results are unreliable.

Forming a valid surface pressure equation for peat soil has proven to be extremely challenging. According to Saarilahti, peat soil can have over 70 different variables that describe the behavior of peat soil [24], thus peat soil is considerable problematic to model.

Field test are still the most accurate way to validate the impact of the machine to the terrain.

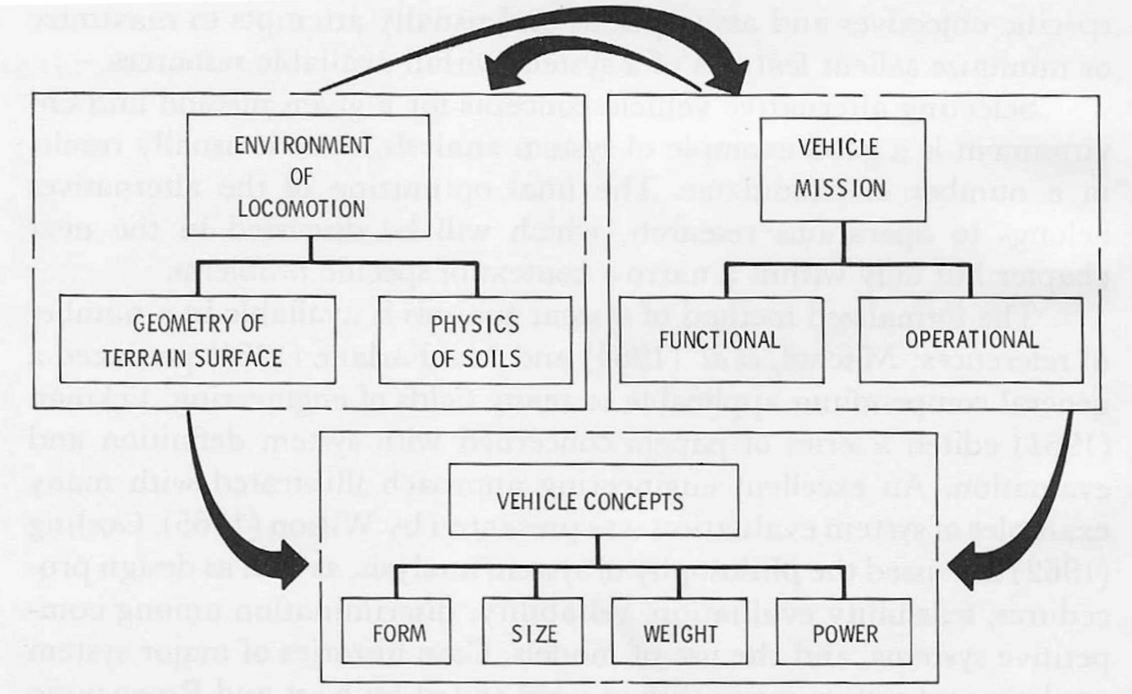


Figure 27. *Terrain-vehicle system for off-road locomotion; system elements.* [58]

The basics of designing an off-road vehicle are still the same as they were in 1969 when Bekker constructed the design guideline to off-road locomotion seen in Figure 27. Simulation of soil behavior could be beneficial for several parts of the off-road machine industry. When the agriculture and forestry industries are in demand of getting more and more efficient, the weight of the machines tend to outgrow the soil resistance. This causes terrain damages that impacts the ecosystem and therefor might also lower productivity in the land.

More efficient simulation models can be profitable for machine manufactures and forest companies. If the terrain effects can be realistically simulated, it can shorten the time used for product development process and the terrain damage can be minimized. Modelling individual harvesting sites can be extremely laborious, but if the terrain characteristics of a certain area are well-known and the soil properties defined, with help of a proper simulation model, the selection of a suitable machine for a site is easier. Field testing seems to be an adequate way to study the machine properties before suitable simulation models are available.

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This document introduces the basic calculations for surface pressure introduced in subchapter 2.2. Some of the equations have been neglected due to their highly empirical nature or poor applicability.

Predefined variables, chosen according to previous studies and existing machine types:

$W := 20 \cdot 10^3 \; kg \cdot 9.81 \; \frac{m}{s^2} = 196.2 \; kN$	machine weight
$n_r := 2$	number of wheel stations in one track
$b := 0.710 \; m$	pneumatic tyre width
$t_t := 0.10 \; m$	track pitch
$A_l := 0.6$	rigid area of link track cleat in propotion to the whole track area
$d := 1.340 \; m$	outer diameter of a pneumatic tyre
$n_{axle} := 2$	number of axles
$B := 1.00 \; m$	track width
$r := \frac{d}{2} = 0.67 \; m$	unloaded radius of the tyres
$L := 1.500 \; m$	wheel hub distance
$h := 0.200 \; m$	tyre carcass height
$\delta := 0.15 \cdot d = 0.201 \; m$	radial deflection of the pneumatic tyre under load
$p_i := 460 \cdot 10^2 \; kPa$	inflation pressure
$z_0 := 0.200 \; m$	sinkage of the loading plate, maximum
$D_h := 0.710 \; m$	hydraulic diameter of the plate
$p_c := 50 \; MPa$	contact pressure
$\hat{n} := 0.88$	Meirion-Griffith variable, moist earth
$\hat{m} := -0.49$	Meirion-Griffith variable, moist earth
$\hat{k} := 78.8 \; \frac{kN}{m^{\hat{n}+\hat{m}+2}}$	Meirion-Griffith variable, moist earth

$$V := \frac{2.5}{3.6} \frac{m}{s} = 0.694 \frac{m}{s}$$ vehicle velocity

$$g := 9.81 \frac{m}{s^2}$$ acceleration due to gravity

Surface pressure:

$$p_{2.1} := \frac{1.26\ W}{2\ n_r \cdot A_l \cdot B \cdot \sqrt{t_t \cdot d}}$$ MMP, link and belt track on rigid road wheels

$$p_{2.2} := \frac{0.5\ W}{2\ n_r \cdot B \cdot \sqrt{\delta \cdot d}}$$ MMP, belt track on pneumatic tyre road wheels

$$p_{2.3} := \frac{W}{2 \cdot n_{axle} \cdot B \cdot L}$$ Littleton & Hetherington MMP model

$$p_{2.5} := \frac{W}{(1.25\ r + L) \cdot B}$$ NGP, bogie track

$$p_{2.6} := \frac{W}{B \cdot d} \cdot \sqrt{\frac{h}{\delta} \cdot \left(1 + \frac{B}{2\ d}\right)}$$ GPI

$$p_{2.7} := \frac{W}{B^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}}$$ GPI, Ziesak & Matthies

Surface pressure with variable machine weight:

$M_1 := 20 \cdot 10^3 \ kg$ $\quad M_2 := 25 \cdot 10^3 \ kg$ $\quad M_3 := 30 \cdot 10^3 \ kg$

$M_4 := 35 \cdot 10^3 \ kg$ $\quad M_5 := 40 \cdot 10^3 \ kg$

$$W := \begin{bmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \end{bmatrix} \cdot g$$

All the tyre widths are replaced with the track width to better compare the models.

$$p_{2.1} := \frac{1.26\ W}{2\ n_r \cdot A_l \cdot B \cdot \sqrt{t_t \cdot d}} = \begin{bmatrix} 281.388 \\ 351.735 \\ 422.082 \\ 492.429 \\ 562.776 \end{bmatrix} kPa \qquad p_{2.2} := \frac{0.5\ W}{2\ n_r \cdot B \cdot \sqrt{\delta \cdot d}} = \begin{bmatrix} 47.256 \\ 59.07 \\ 70.884 \\ 82.698 \\ 94.512 \end{bmatrix} kPa$$

$$p_{2.3} := \frac{W}{2 \cdot n_{axle} \cdot B \cdot L} = \begin{bmatrix} 32.7 \\ 40.875 \\ 49.05 \\ 57.225 \\ 65.4 \end{bmatrix} kPa \qquad p_{2.5} := \frac{W}{(1.25\ r + L) \cdot B} = \begin{bmatrix} 83.936 \\ 104.92 \\ 125.904 \\ 146.888 \\ 167.872 \end{bmatrix} kPa$$

$$p_{2.6} := \frac{W}{B \cdot d} \cdot \sqrt{\frac{h}{\delta} \cdot \left(1 + \frac{B}{2\ d}\right)} = \begin{bmatrix} 171.146 \\ 213.933 \\ 256.72 \\ 299.506 \\ 342.293 \end{bmatrix} kPa \qquad p_{2.7} := \frac{W}{B^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}} = \begin{bmatrix} 294.942 \\ 368.678 \\ 442.413 \\ 516.149 \\ 589.884 \end{bmatrix} kPa$$

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Master of Science Thesis
Appendix A